The CODALEMA experiment

COsmic-ray Detection Array with Logarithmic ElectroMagnetic Antennas

The Radio-Detection of EAS

P. Lautridou – SUBATECH

@ NANÇAY
(some tens dipôles)

@ AUGER-Sud
(3 dipôles in 2007)

=> PHASE 1 (2002-05): Enlightenment of the Methode
=>PHASE 2-3: (2006-08): Energy Calibration from 10^{16} to 10^{18} eV

The CODALEMA collaboration :

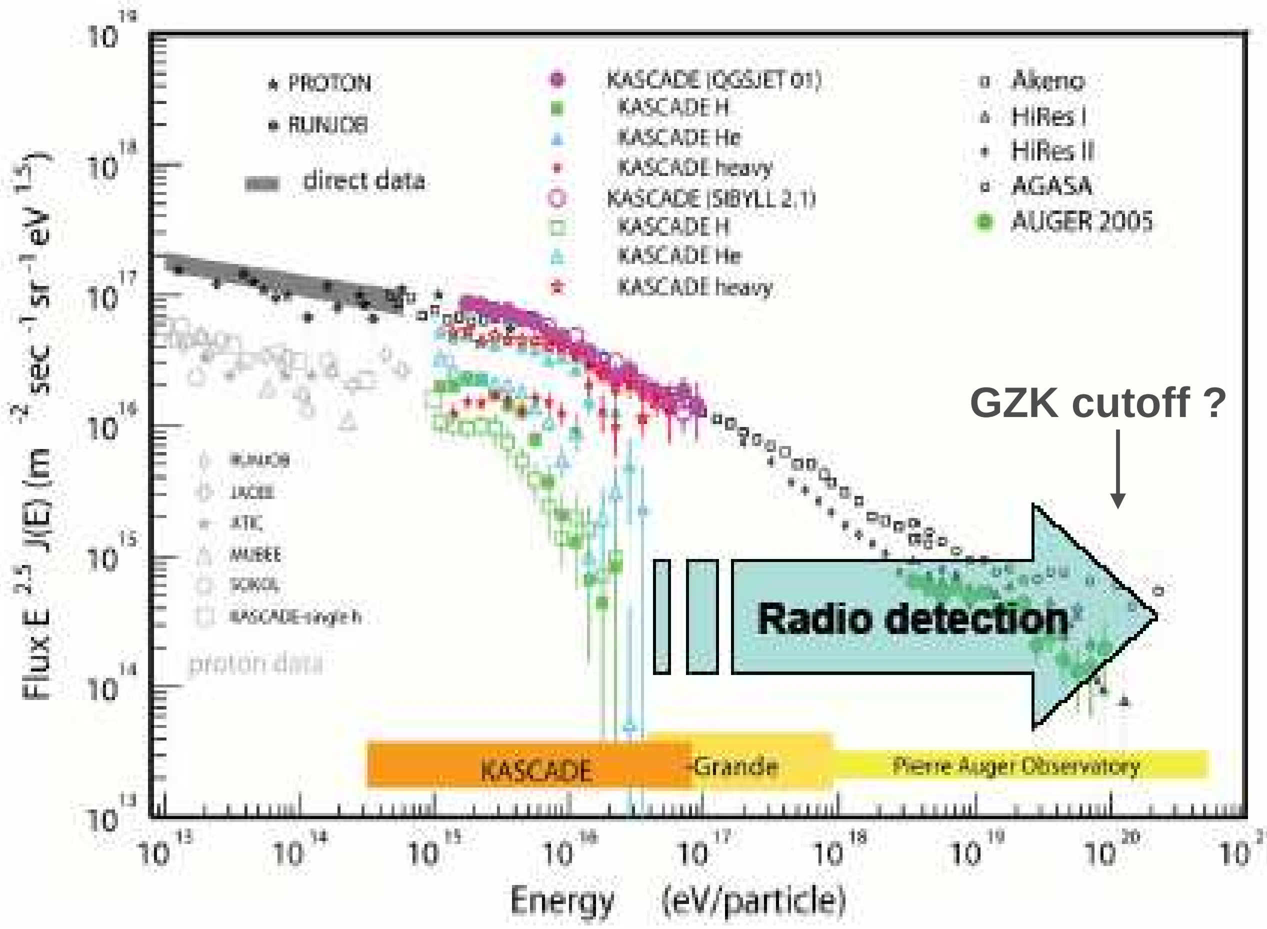
3 Instituts – 8 Laboratories

SUBATECH Nantes (IN2P3, 2002)
Obs. de Paris-Meudon (INSU, 2002) - Station de Nançay (INSU, 2002)
LAL Orsay (IN2P3, 2004) - ESEO Angers (2004)
LPSC Grenoble (IN2P3, 2005)
LAOB Besançon (INSU, 2006) - LPCE Orléans (INSU, 2006)
+ support of the Lab. of AUGER-France for the tests @ AUGER-Sud

<u>UHCR studies</u>
address the problematic of the

ORIGINE
&
NATURE
of the cosmics

Complementary to hybride techniques
Optical Cerenkov
Surface particles det.



<u>Radio-detection:</u> longitudinal development, macroscopic observables, long range detection, inclined showers, cheap, high duty cycle

Contents

- **Radio-emission framework**
- **Experimental méthodologies & CODALEMA performances for transients**
- **CODALEMA EAS Results**
- **LOPES EAS results**
- **Present & futur developments of radio-detection with CODALEMA**

Radio-emission framework

La radiodétection

1962: **Prédiction théorique** - effet Askar'yan

1964-65: **Première expérience** - T.C. Weekes

Milieu 70 ': **Méthode délaissée** difficultés d'interprétation et de détection + succès d'autres techniques

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Fin 90 ': **Redécouverte dans milieux denses (glace, sel) =>neutrinos**

En 1999: **Preuve du principe sur accélérateur (sable, D. Saltzberg,)**

En 2000 : **Expérience sur CASA-MIA (K.Green et al., 2003, N.I.M. A, 498)**

En 2002 ← **Expérience LOPES sur KASCADE**
Expérience CODALEMA de SUBATECH

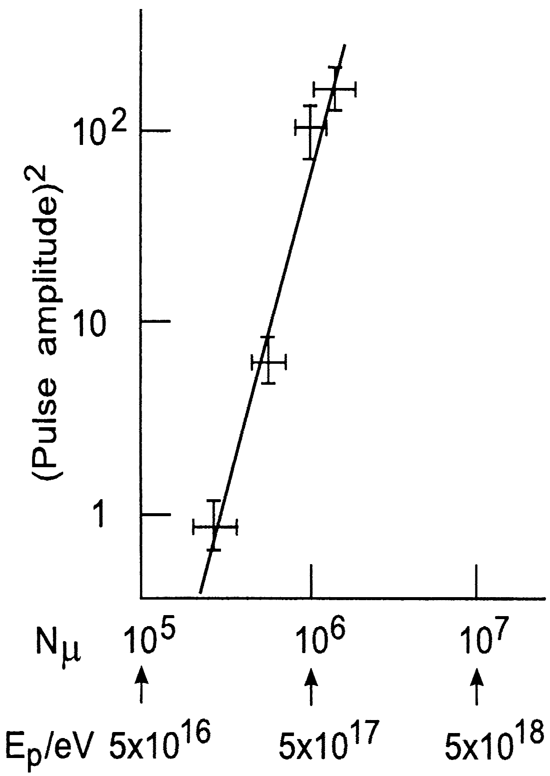
En 2005 : ← **H. Falcke et al., Nature, May 19, 2005**
P. Lautridou et al. NIM A555 2005 & astro-ph 2003-2005

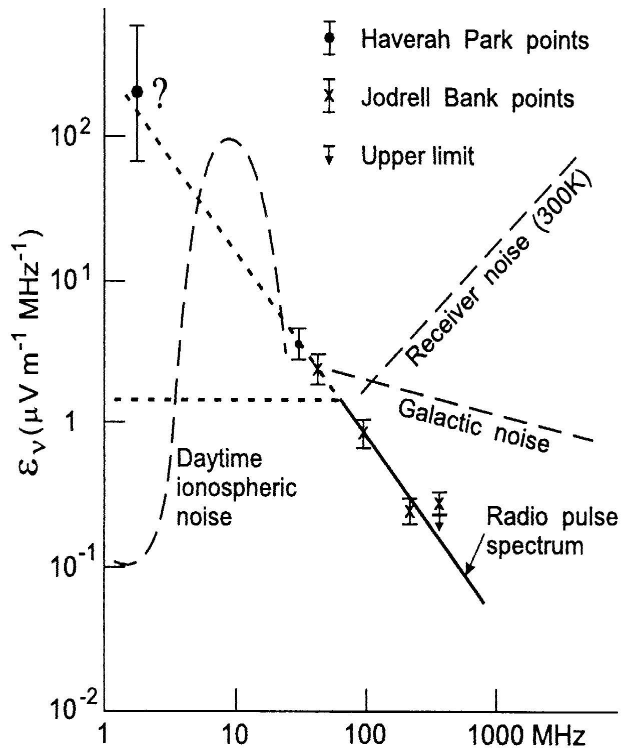
En 2006-07: CODALEMA en prospectives sur PAO
En 2008: CODALEMA sur 3 continents: Am, Eur, Asie?

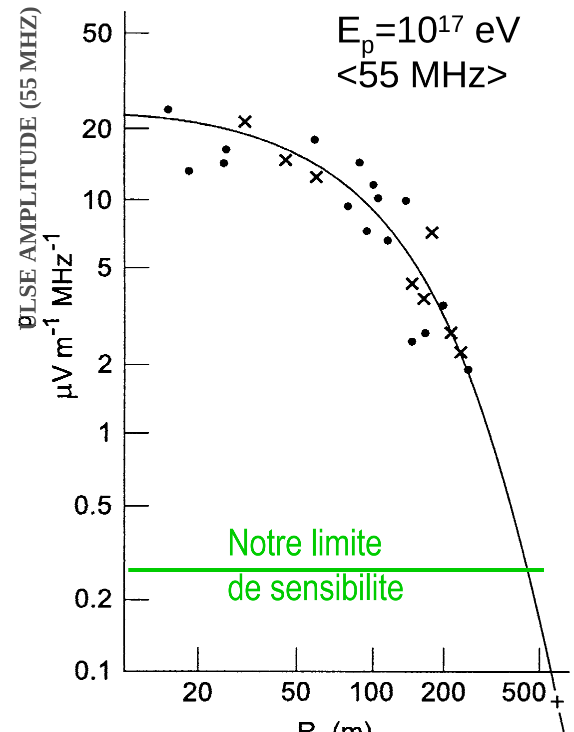
Les résultats expérimentaux de 1970

H.R Allan, Prog. in Elem. Part. Cosmic Ray Phys., 10 (1971), p.171

- **Développements théoriques basés sur une analyse fréquentielle du signal**
- **1 antenne résonante (Δf=1 MHz)**
- **en coïncidences avec des détecteurs de particules chargées au sol**





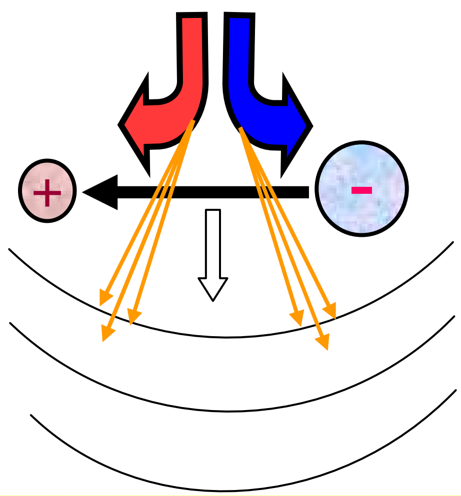


Des certitudes mais ….des incohérences (Haverah Park, Yakutsk,…)

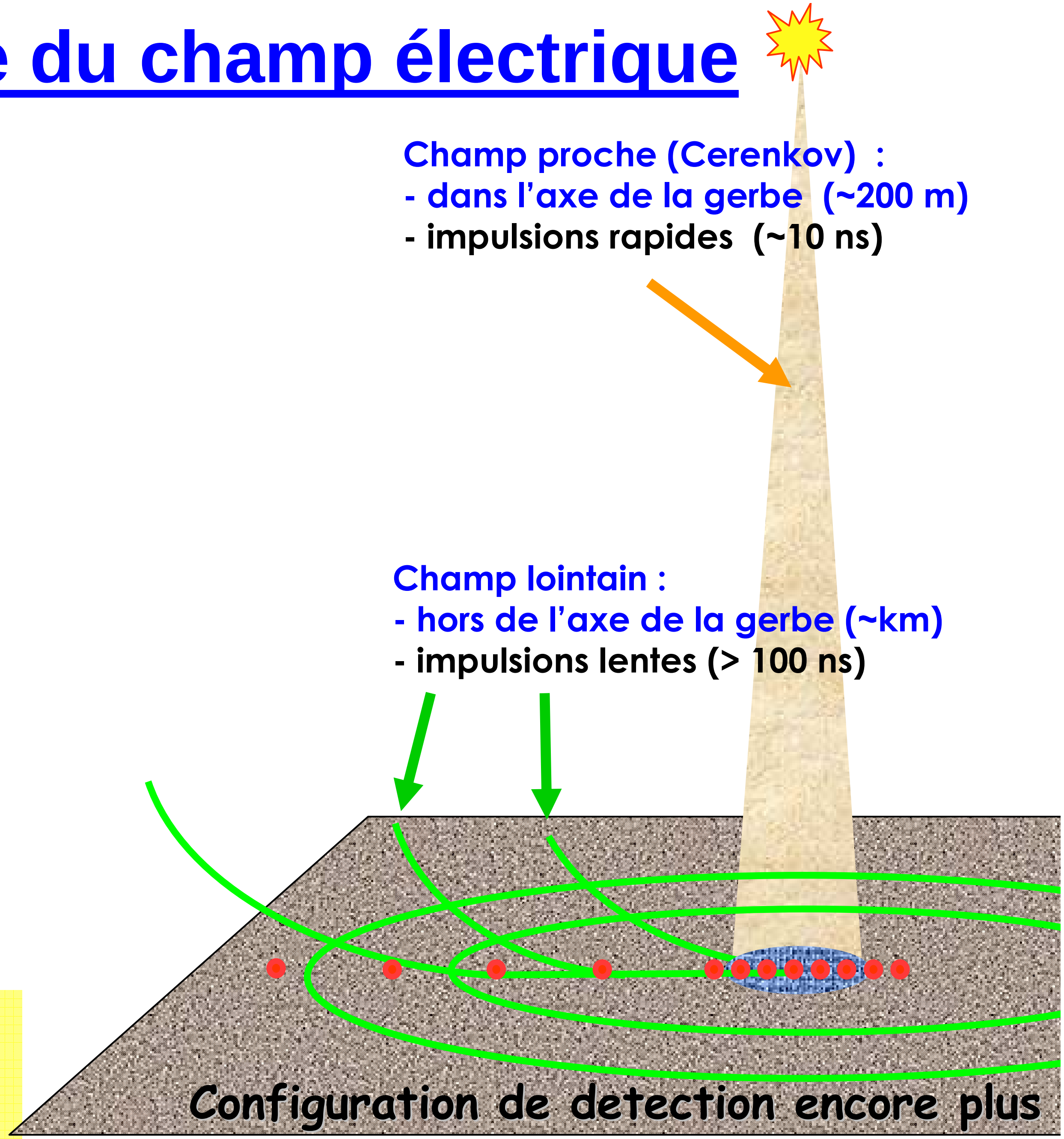
Origine du champ électrique

90% de γ (>50keV)
9% d'ē (>250keV)
0,9% μ (>1GeV)
0.1% hadrons

- Excès de charge: e-/e+
  monopole
- Effet géomagnétique F=qVxB
  dipole



- ◆ Emission par courant Dipolaire ou Synchrotron ?
- ◆ Emission Cerenkov ?



Configuration de detection encore plus favorable pour les gerbes inclinées

Théorie: quelle approche?

Analyses en fréquence (1970) → en forme d'onde (2000)
Cadre préliminaire (1970) → «coming out» théorie (2007)

- **Semi-empirique**

Description macroscopique (lois de comportement simples + modèles analytiques): SUBATECH, Obs. de Paris, KVI

- **Monte-Carlo élaboré**

Codes CORSIKA, AIRES, CONEX ? & modèles semi-analytiques d'émission radio: SUBATECH, LAL, LPSC

- **Code dédié LOPES (T. Huege 2004)**

Description microscopique de l'émission synchrotron (FZK)

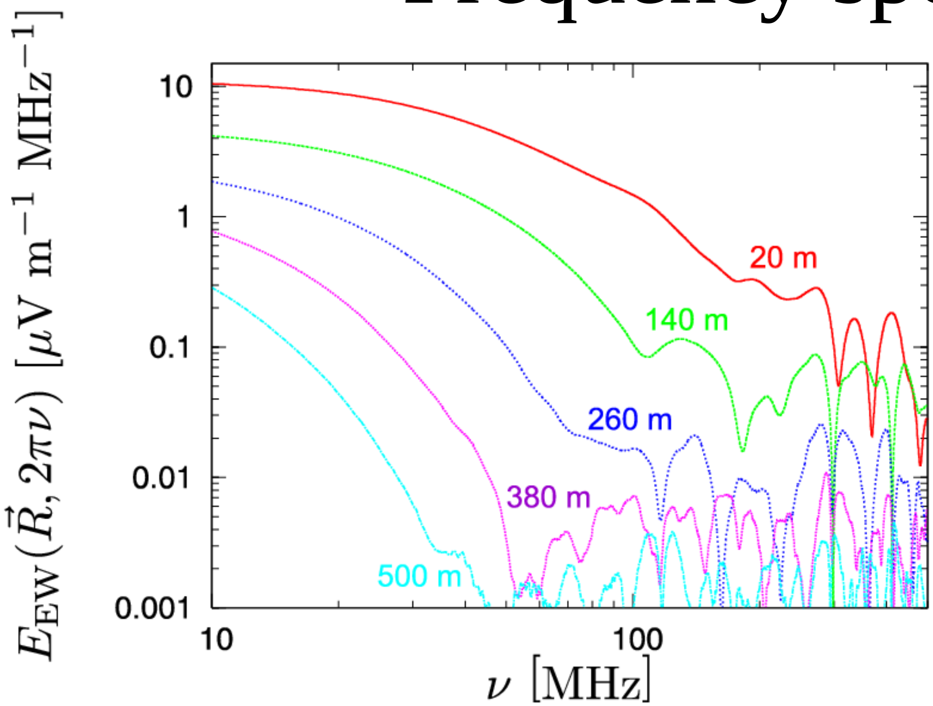
Trouver les variables discriminantes!!

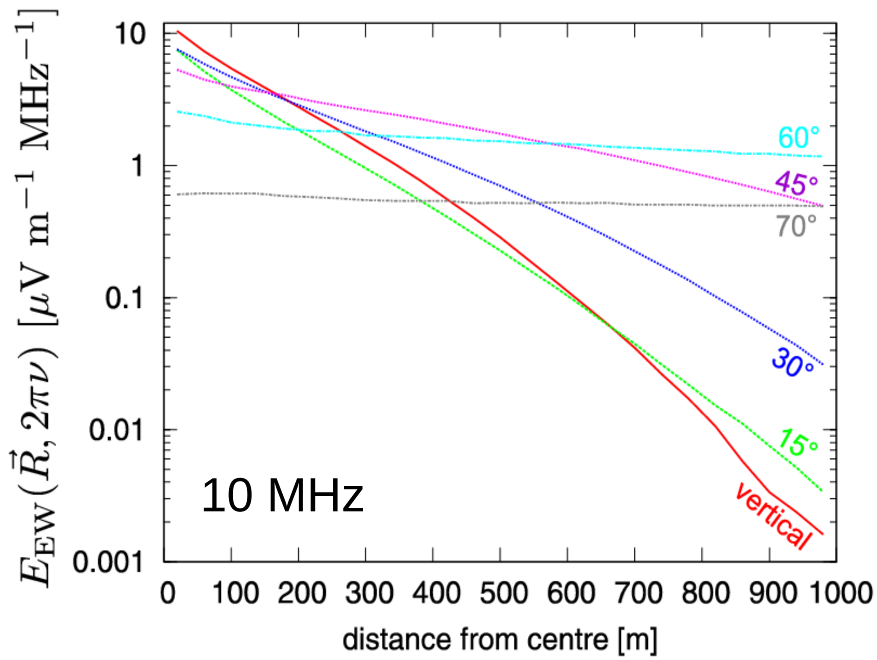
- Asymétrie nord-sud ?
- Extension latérale ?
- Polarisation ? (longitudinale? Transversale?) (Mesure des états de polarisations en cours sur CODALEMA)

T. Hugues 2004

(based on microscopic synchrotron calculations)

Frequency spectra @10^{17} eV





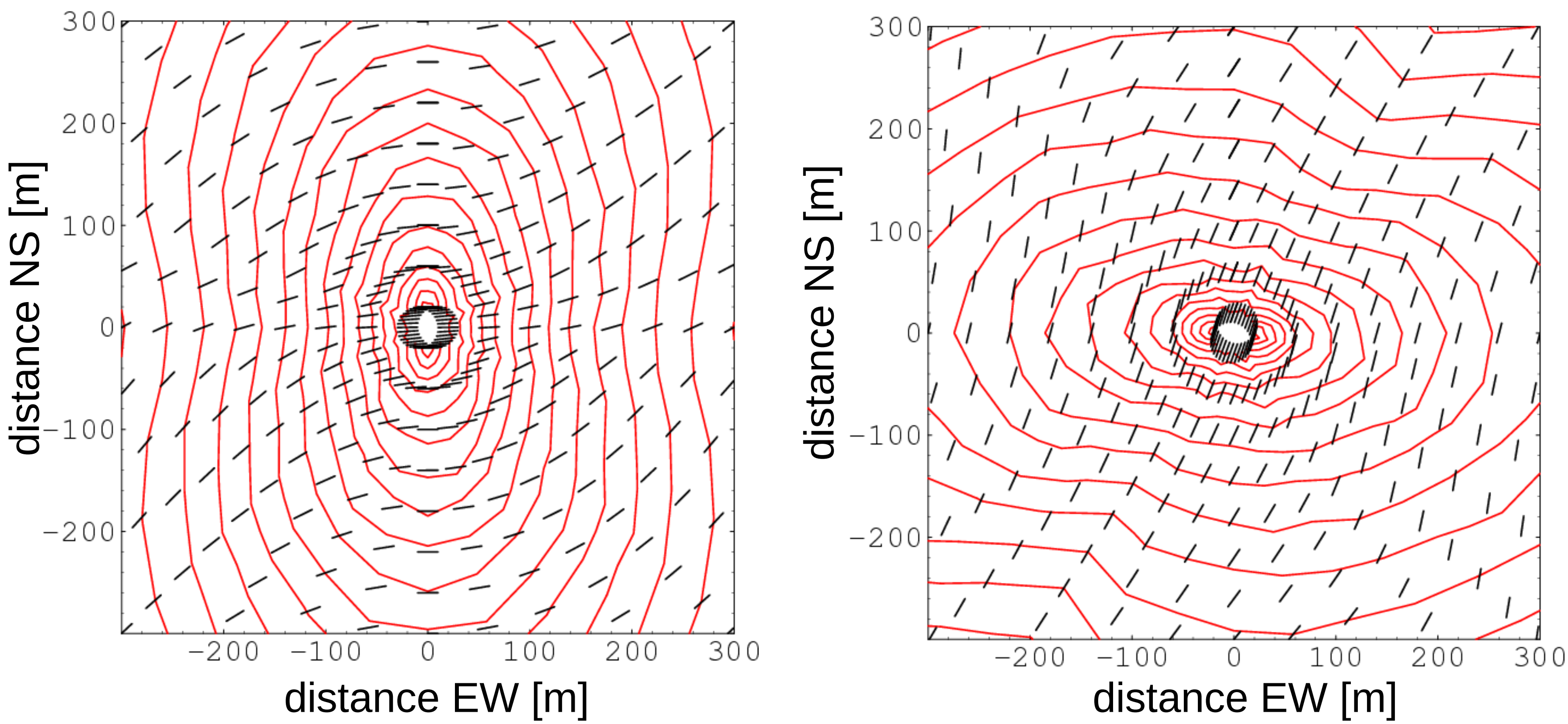
- For vertical showers
- 10 MHz: very coherent
- 55 MHz: coherence only up to ~ 300 m

- Favourable for inclined showers
- Approx. Exponential scaling

But frequency spectra seem not models discriminating…

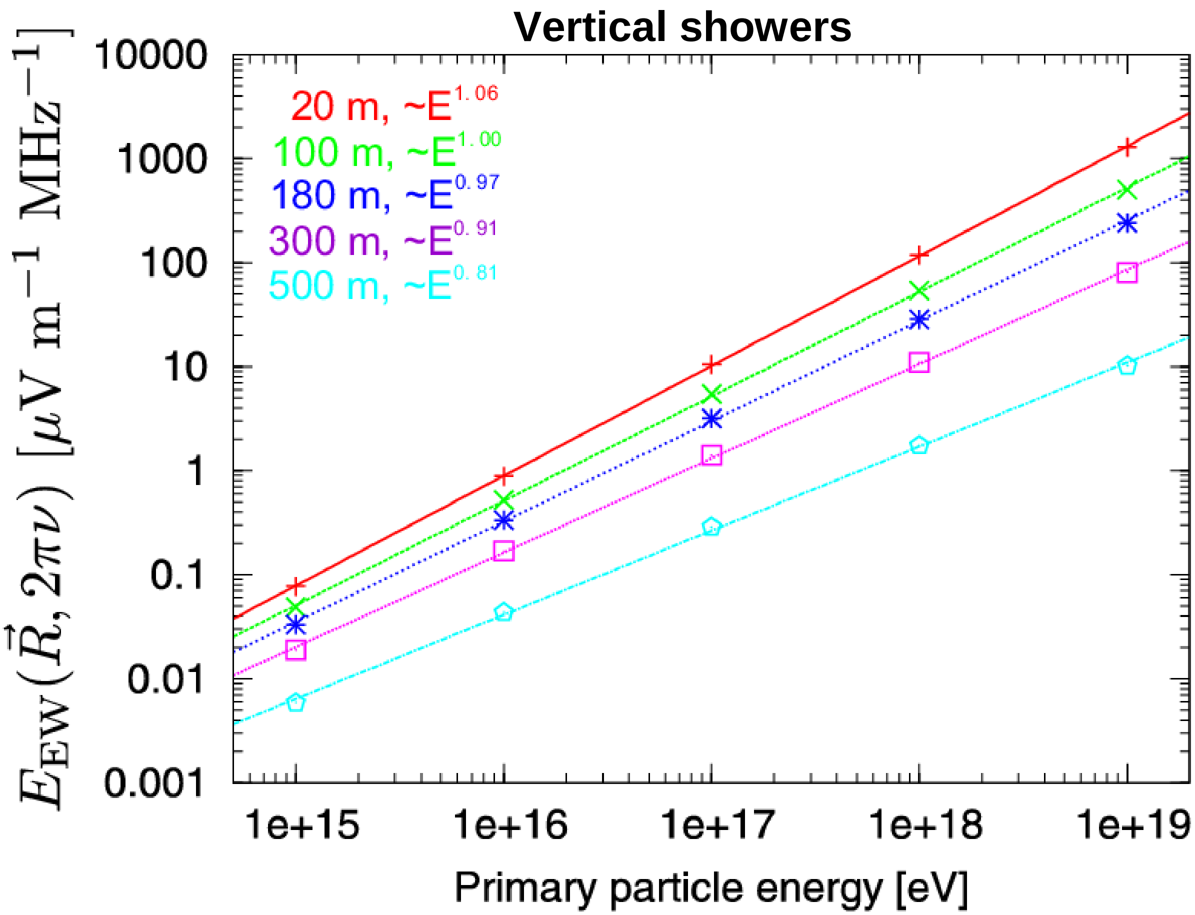
T. Hugues: Polarisation @10^{17} eV, 10 MHz

45° zenith angle, 0° azimuth **45° zenith angle, 90° azimuth**



- most power in polarisation direction perpendicular to B-field and shower axes
- But North-South asymmetry not predicted !?

T. Hugues: Scaling with E_p @10 MHz

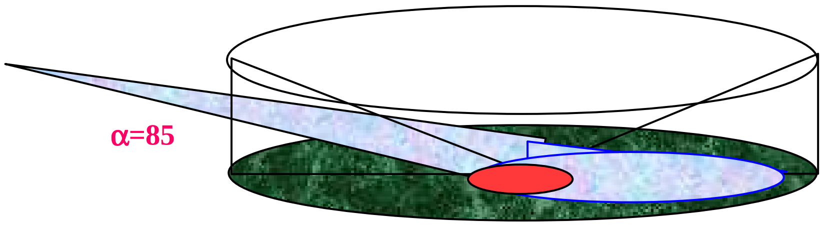


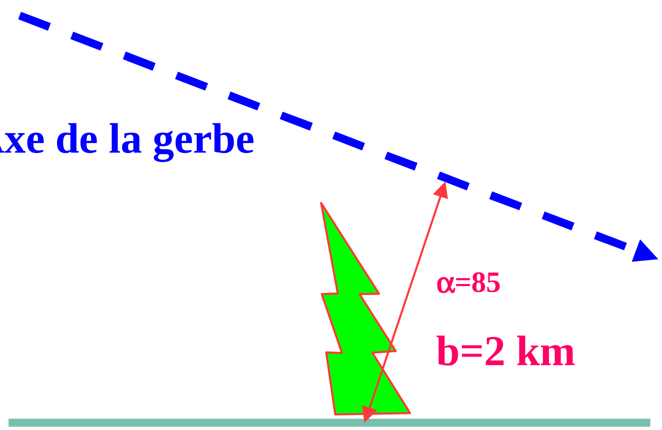
- Nearly linear scaling with Ep
- Flatter at higher distances

T. Gousset et al. (2004):Simulations de gerbes horizontales (basées sur des grandeurs macroscopiques)

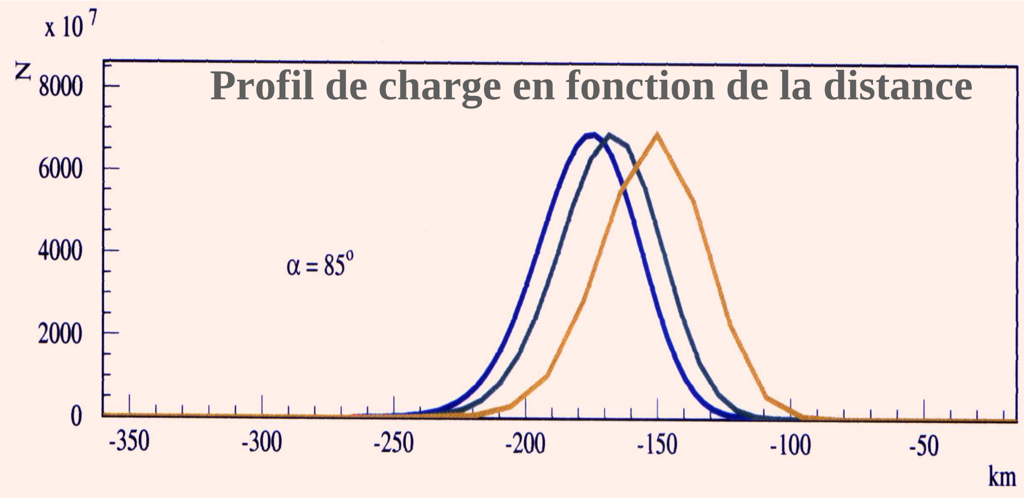
Détection à très longue portée

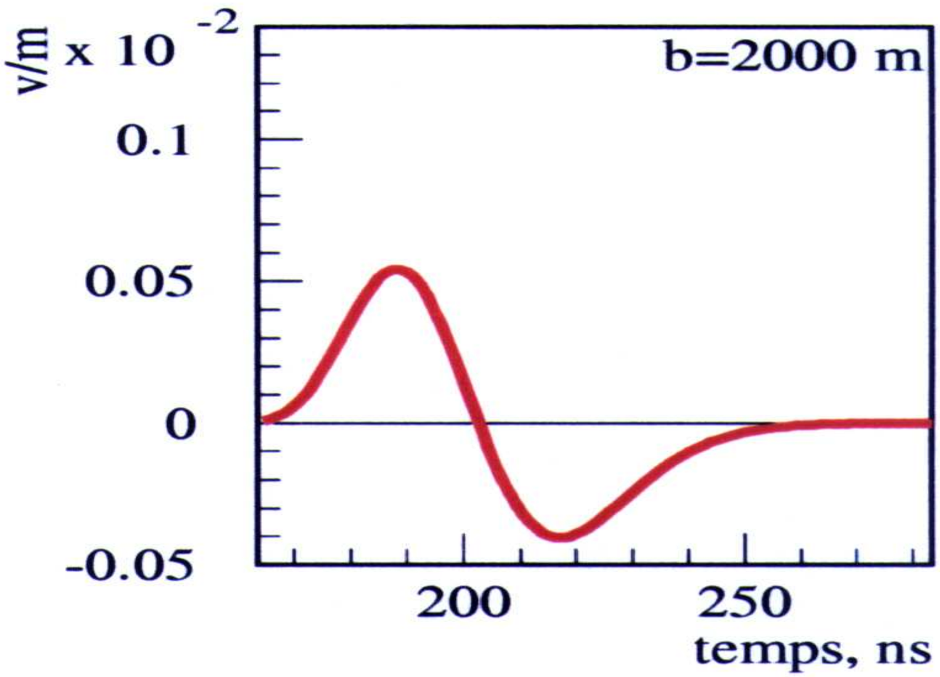
- **Cône d'éclairement**
- **Amplitude + temps d'arrivée**
- **Détection de ν?**





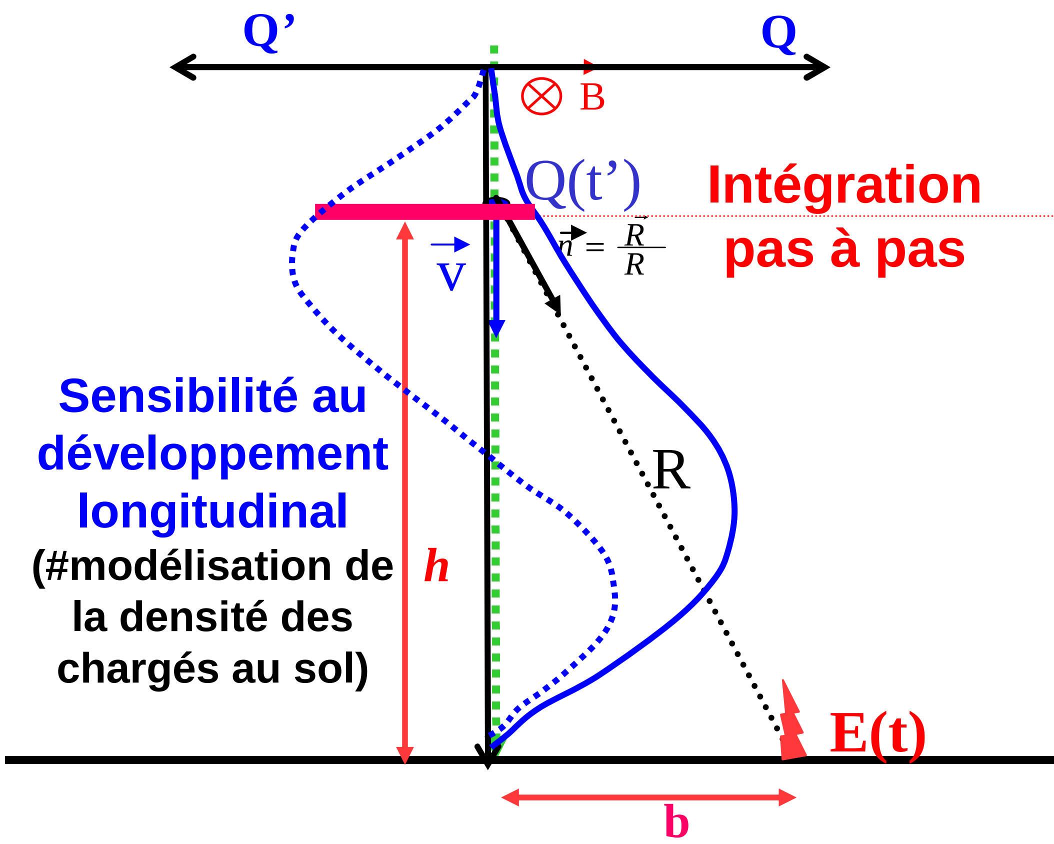
E=10^{20} eV + 10 % Excès de charge (0.7 10^{10} e^-)





K. Werner et al. (2007)

(basés sur des grandeurs macroscopiques de la gerbe)



incluant:

⇒Extension longitudinale des secondaires

⇒Extension latérale

⇒Épaisseur de la galette

⇒Distribution en γ

⇒Vision macroscopique de la source du champ électrique: Courant dipolaire
(en cours de publication)

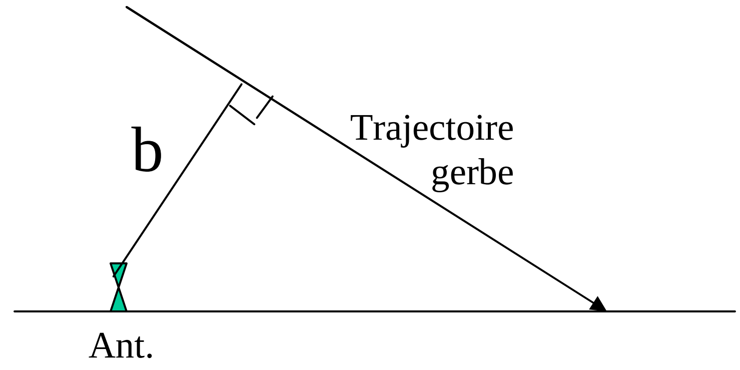
$$E(t,r) = \frac{1/4\pi\varepsilon\ \Sigma_{t'}\ (1-v^2/c^2)\ q(t')\ .(\mathbf{R}-R\mathbf{v}/c)}{|R-\mathbf{R.v}/c|^3} + \frac{1/4\pi\varepsilon c\ \Sigma_{t'}\ q'(t')\ (\mathbf{R}-R\mathbf{v}/c)}{(R-\mathbf{R.v}/c)\ |R-\mathbf{R.v}/c|^3} + \frac{1/4\pi\varepsilon c\ \Sigma_{t'}\ q(t')\ \mathbf{R}\wedge[(\mathbf{R}-R\mathbf{v}/c)\wedge\mathbf{v'}]}{|R-\mathbf{R.v}/c|^3}$$

Experimental méthodologies & CODALEMA performances for transients

La démarche expérimentale

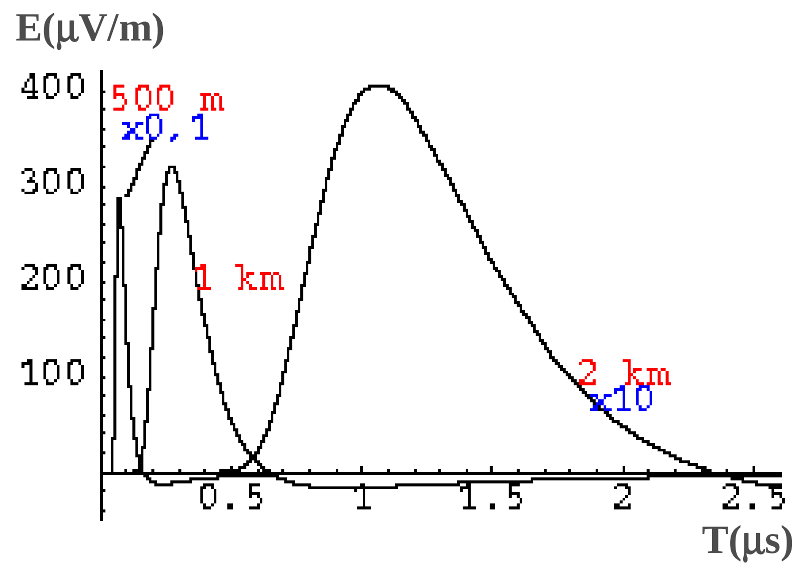
•**Simulation théorique:** Informations contenues dans la forme du signal

- •Amplitude (>1µV/m) => énergie
- •Durée (~100 ns) => paramètre d'impact (b)
- •Forme d'onde => nature des particules



•**Mesures expérimentales:**

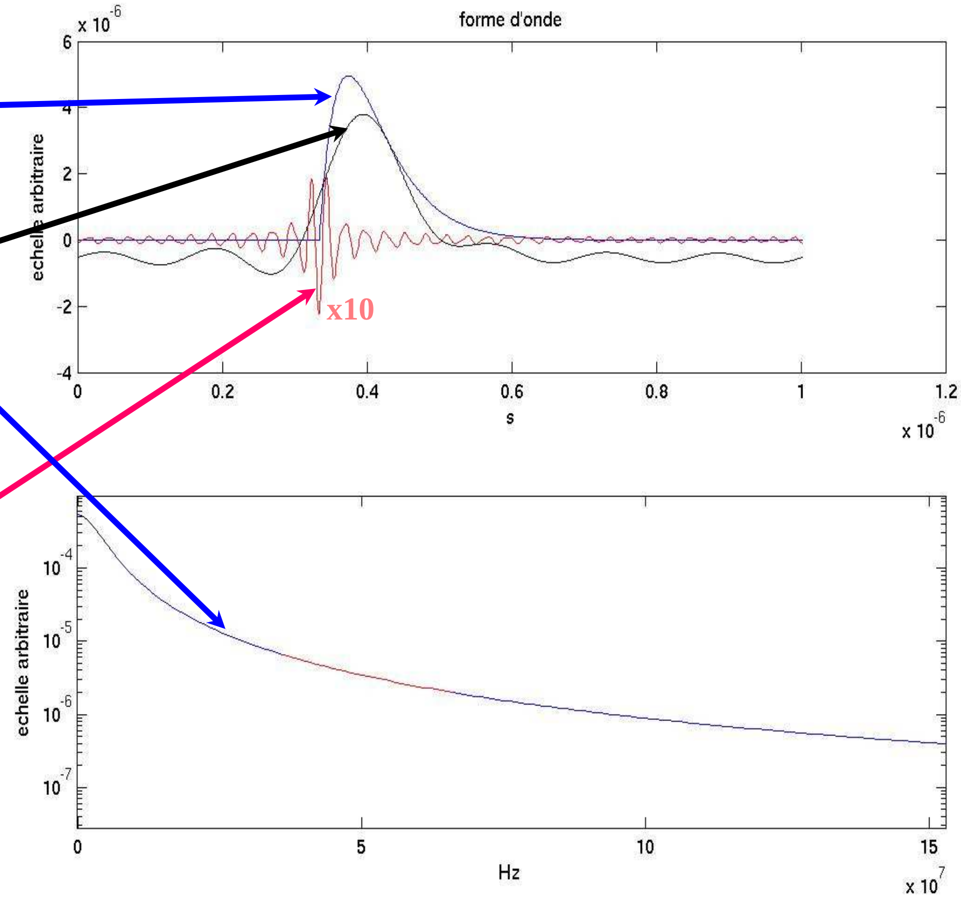
- •Evts rares (trigger~10^{-3} Hz)
- •Analyse temporelle du signal=>direction d'arrivé
- •Analyse de l'amplitude =>Extraction de l'énergie du primaire



La Recherche des impulsions

- **Impulsion => Signal à durée finie**
    - x(t)=t.exp(-t/tau)

=> spectre large bande



- **Filtre 0.5-5MHz**
    - Forme du transitoire
    - beaucoup de puissance

=> énergie

- **Filtre 35-65MHz**
    - front de montée
    - peu de puissance

=> information temporelle

Mais le signal réel est dans du bruit: capteur, RFI, signal galactique, etc…

The CODALEMA Techniques for Transient Detection

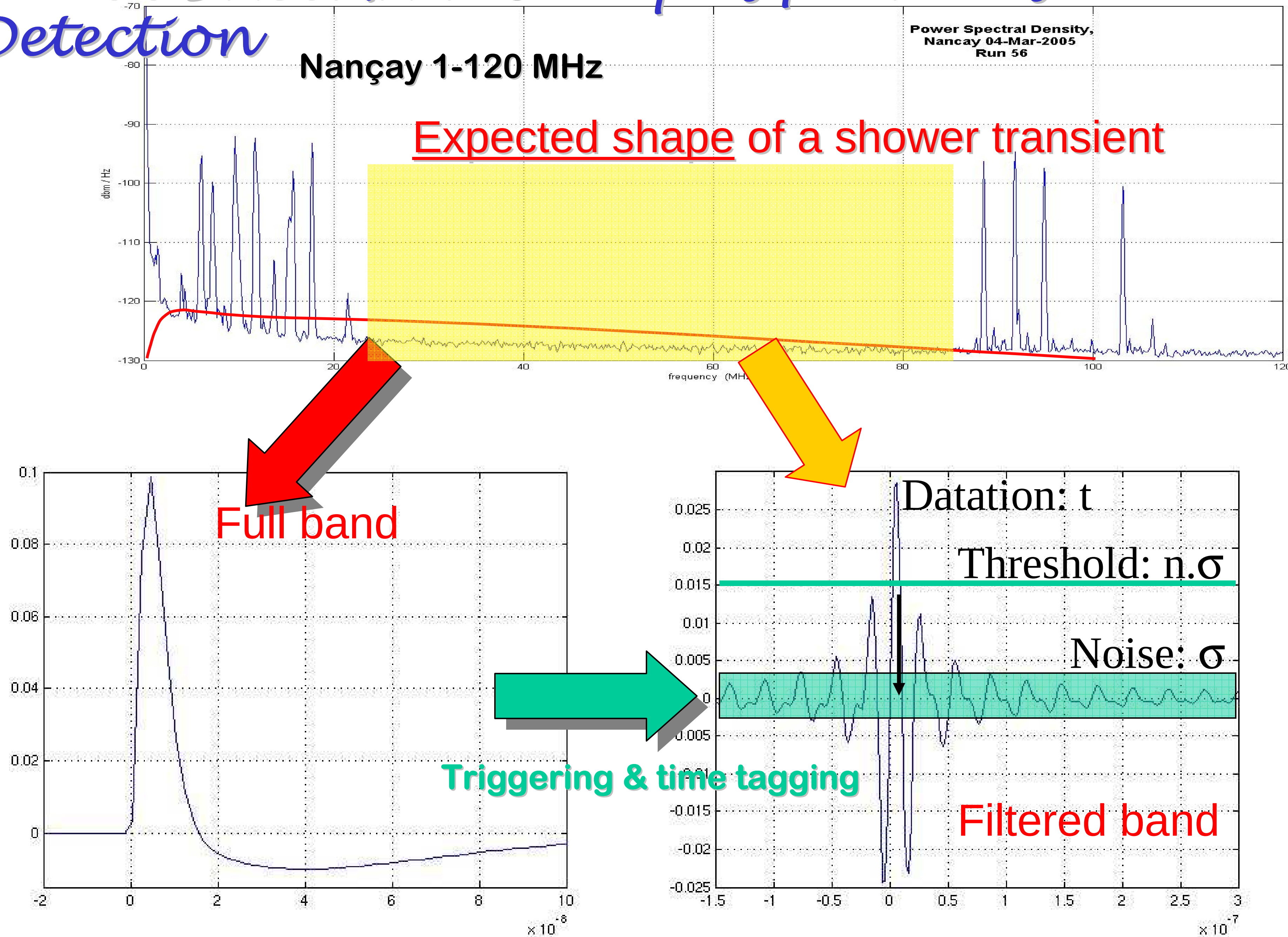
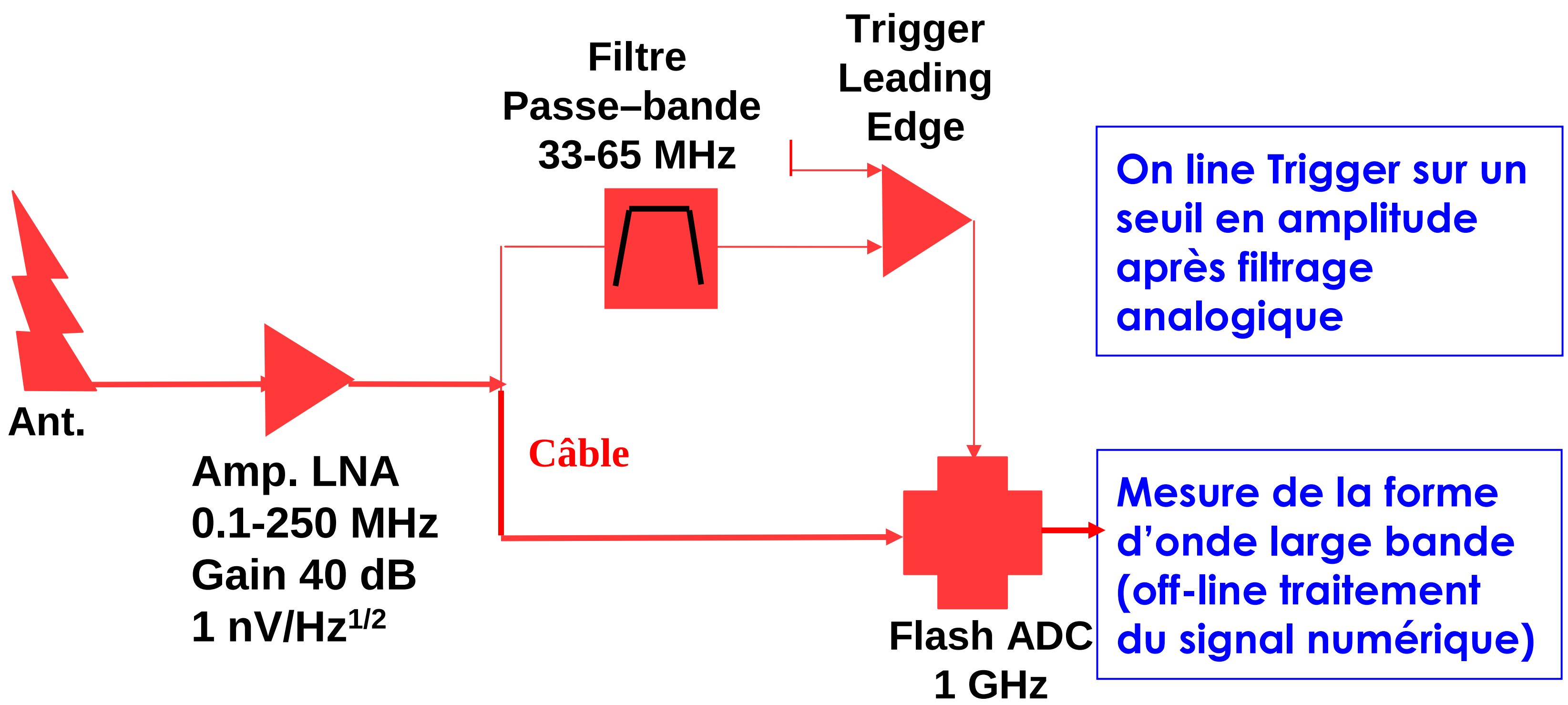


Schéma du Trigger radio de CODALEMA @ Nançay



Stratégie en 2 étapes:

1. **Taux de trigger On-line >> Taux de transitoires EAS…**
2. **EAS identifiés off-line par analyse de la forme d'onde utilisant un critère de sélection par le nombre d'antennes touchées**

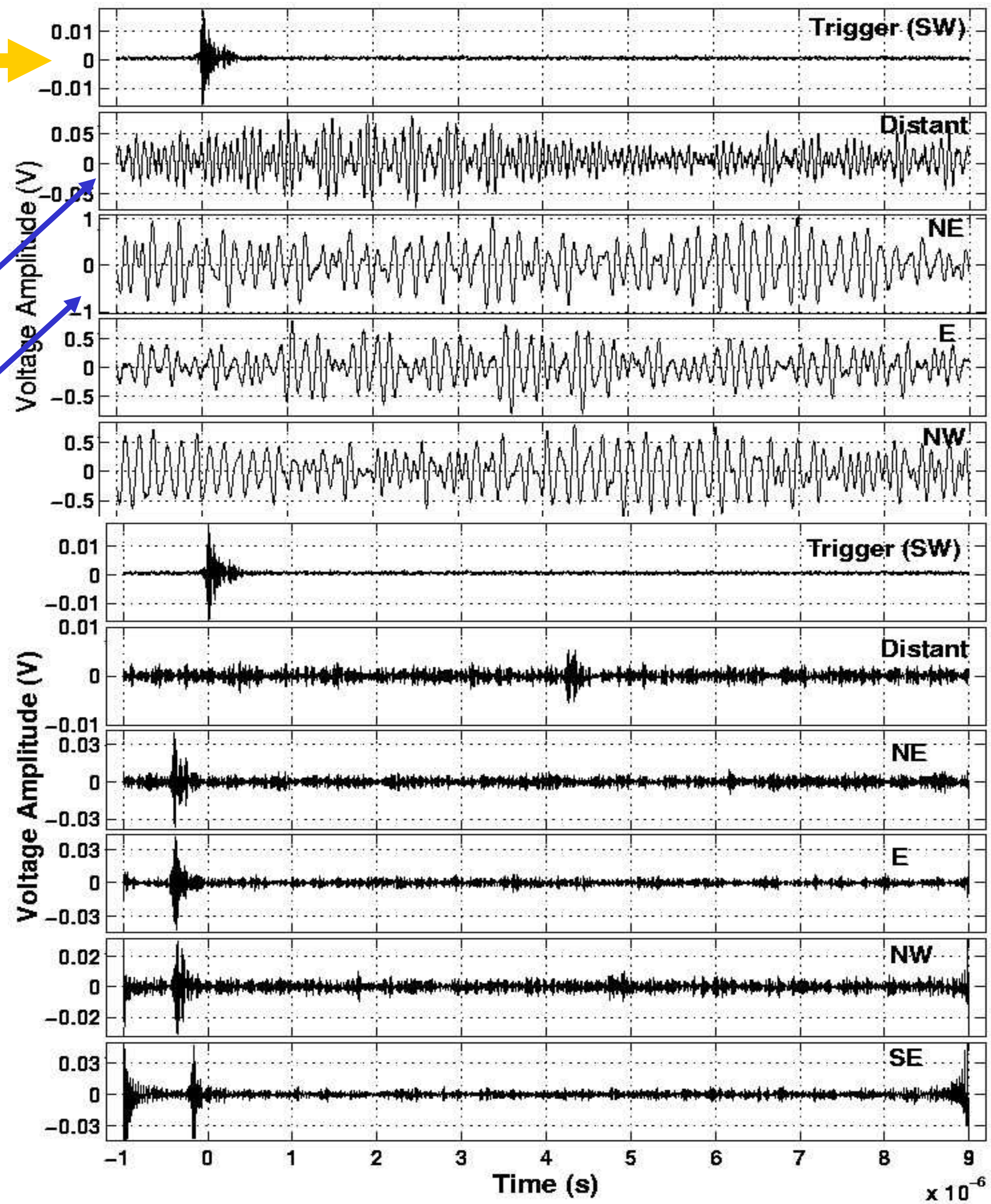
Transient recognition

1 trigger antenna
voltage threshold on a devoted filtered antenna (33-65 MHz)

1 distant antenna (1 km) @10-100 MHz
5 broad band antennas (1-100 MHz)

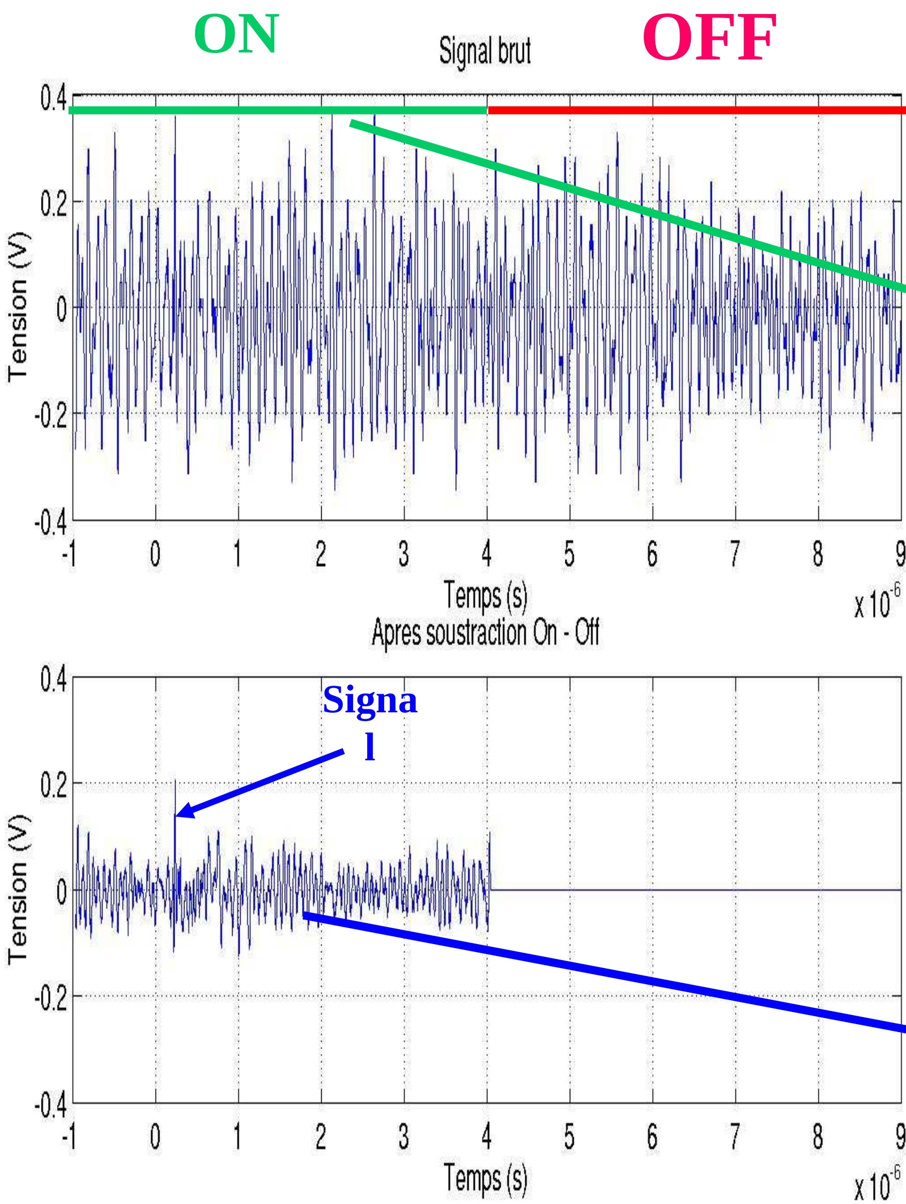
With Flash ADC 8bits - 500 MS/s - 10µs

After 33-65 MHz off-line numerical filtering



Principe d'extraction de la forme d'onde large bande

via un filtrage FFT + une methode On-Off



•**Par fft sur la partie OFF :**
$R_{off}(f)\ e^{\,j\Phi off(f)}$

•**Par fft sur la partie ON :**
$R_{on}(f)\ e^{\,j\Phi on(f)}$

Hypothèse:

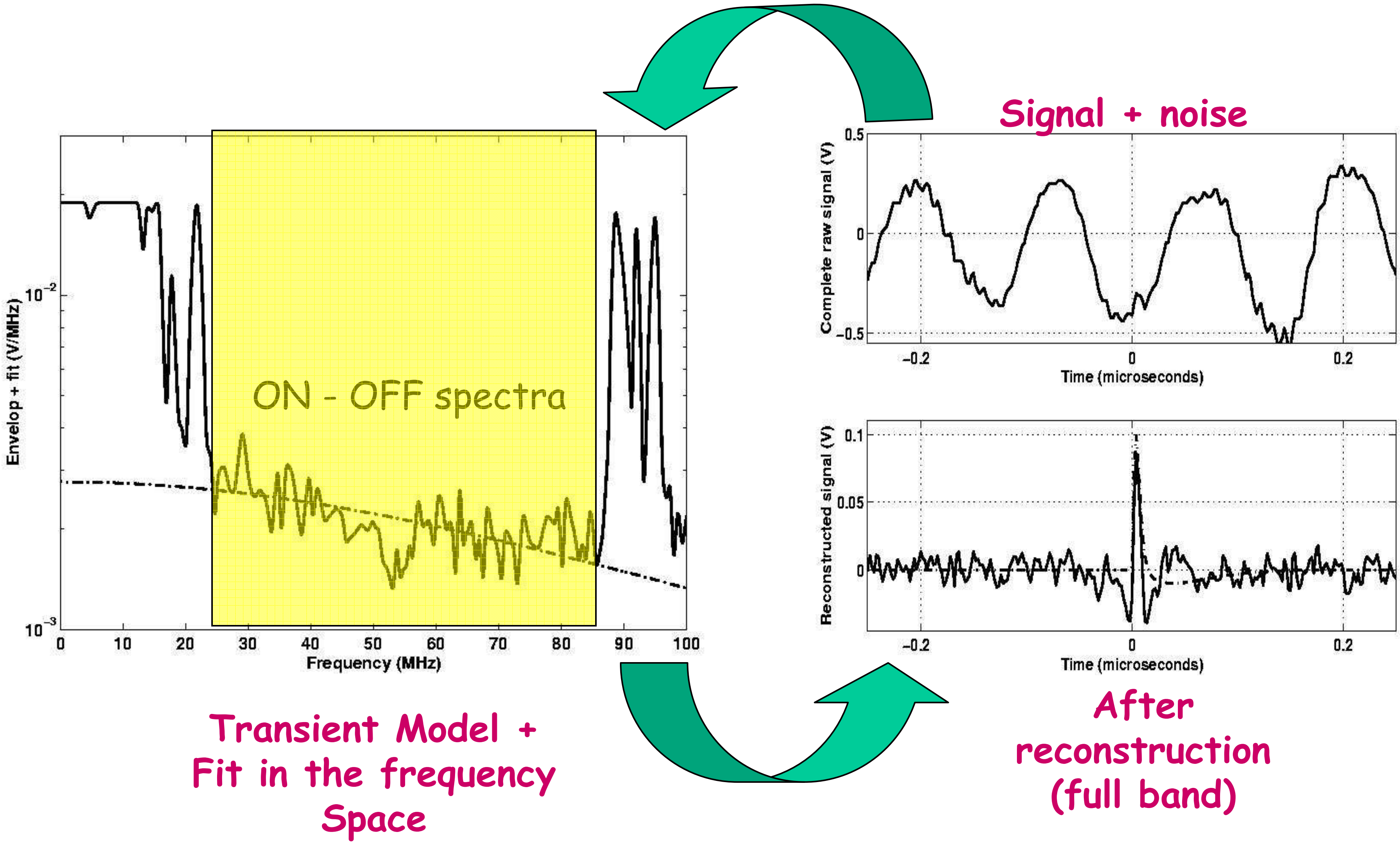
- Émetteurs RF stationnaire
- Signal recherché faible

=> $R_{on/off}(f) = R_{on}(f) - R_{off}(f)$

• **Par** fft^{-1} **de** $R_{on/off}(f)\ e^{\,j\Phi on(f)}$

Principe d'extraction de la forme d'onde large bande

via un filtrage FFT + un modèle de transitoire

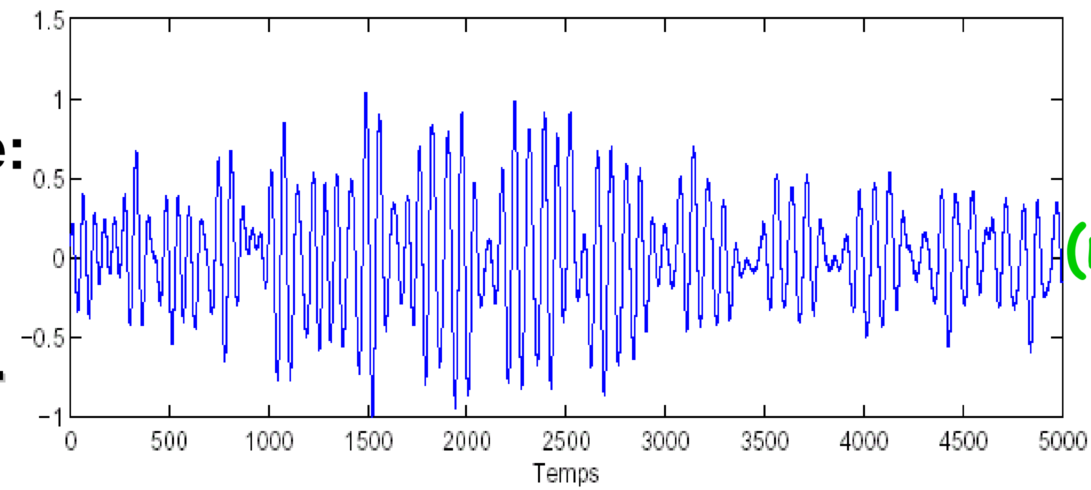


New Waveform Recovery at large Band

Extraction via Linear Predictive Coeficients

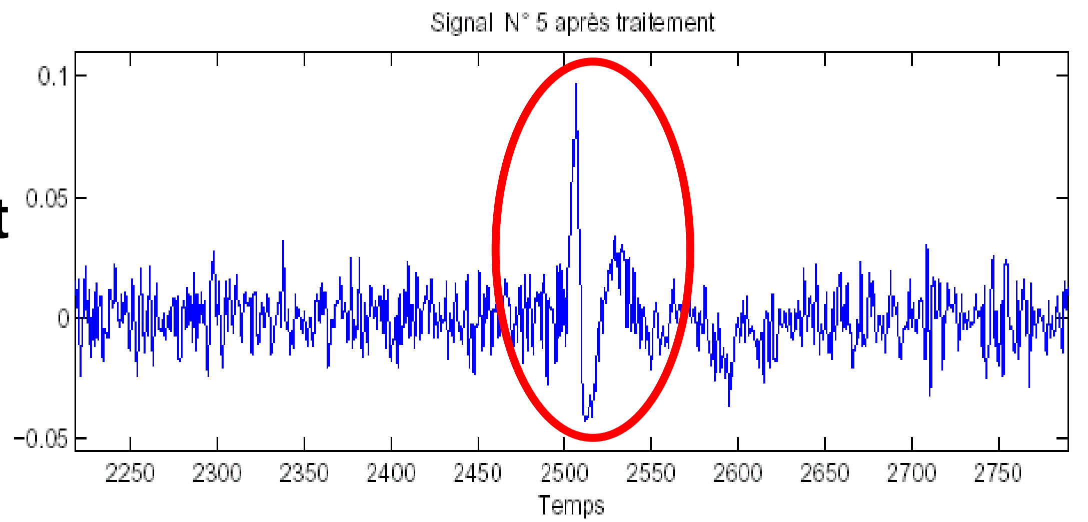
(Adaptative optimal filtering)

=>Partial shape: full band recovery need complet filter ...



Signal (noise+ pulse)

=>Time resolution: ~ns adding Wavelet Analysis

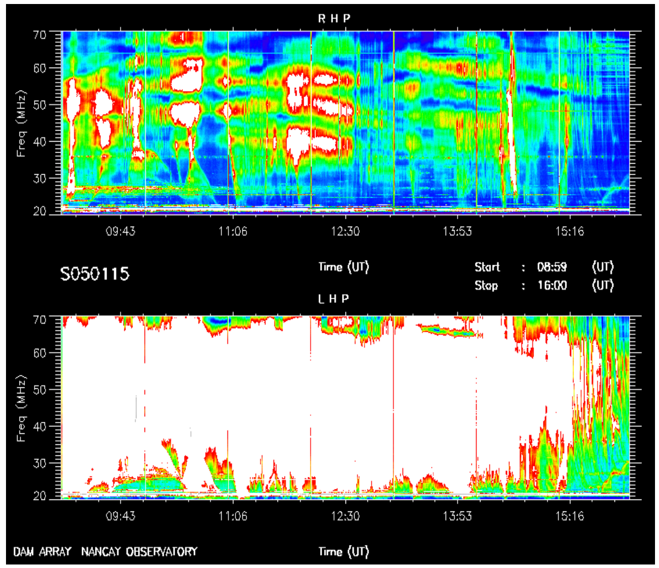


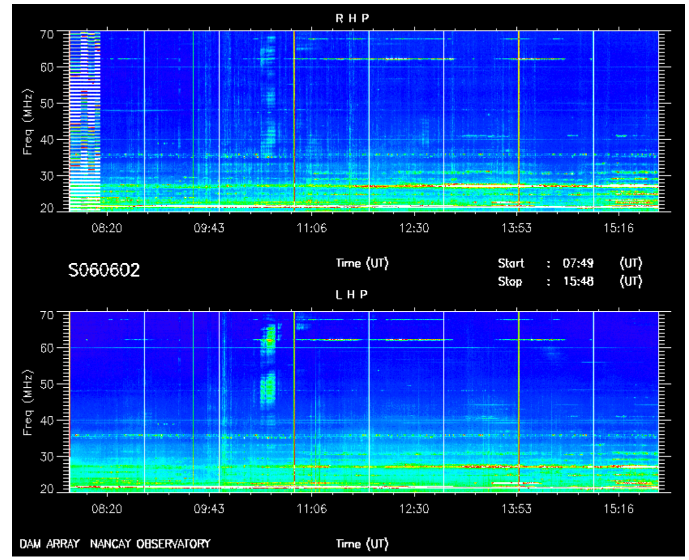
Remaining signal

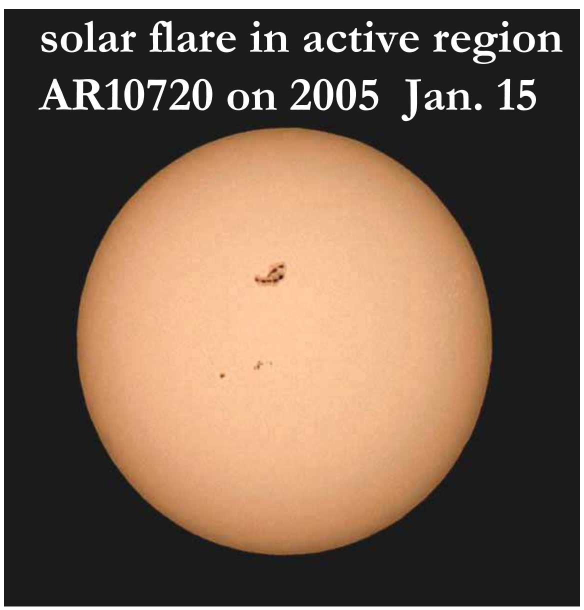
Triangulation performances (1)

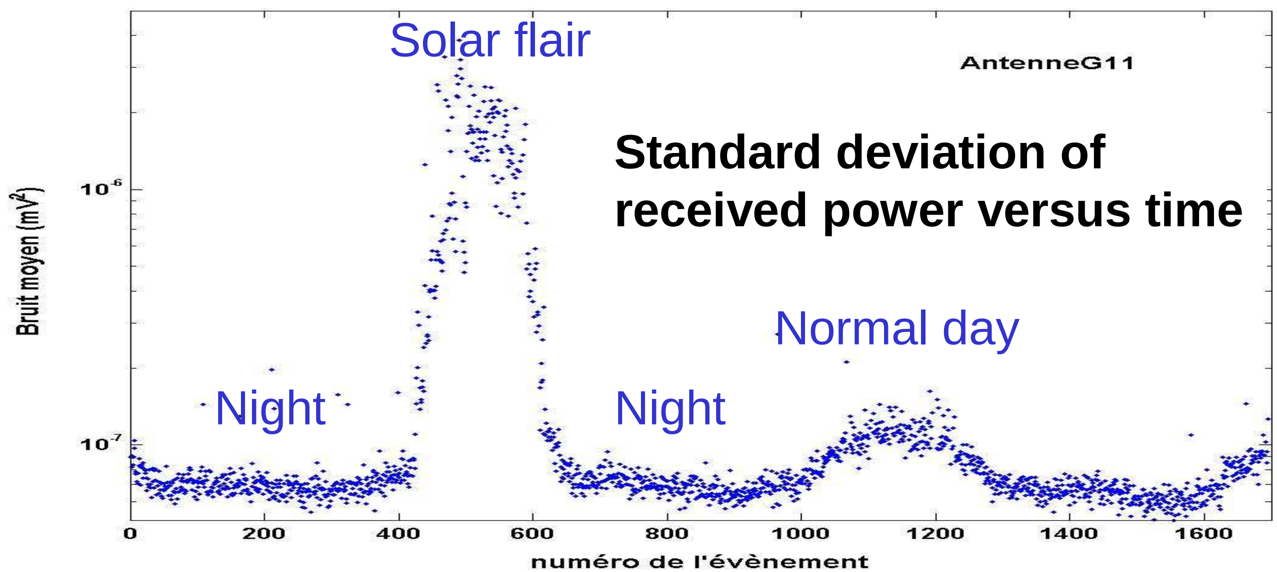
(using Solar bursts)

DAM sun survey
15/01/05
&
02/06/06



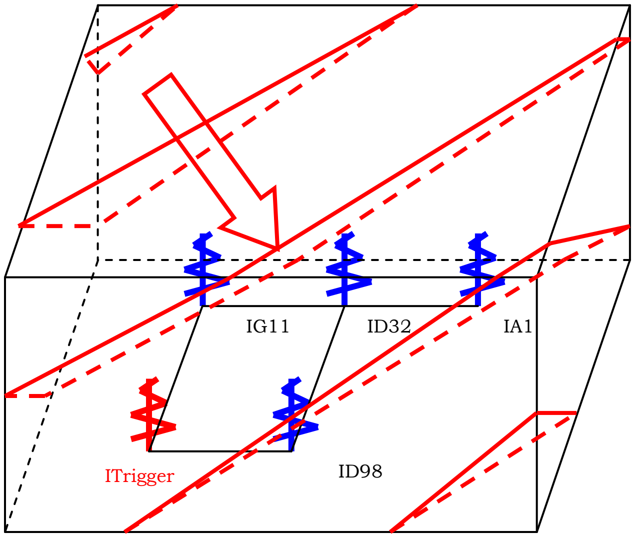




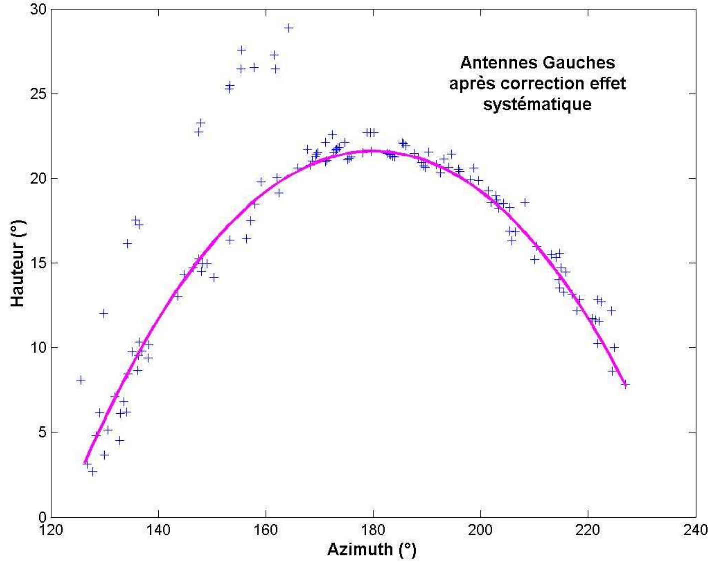


Triangulation performances (2)

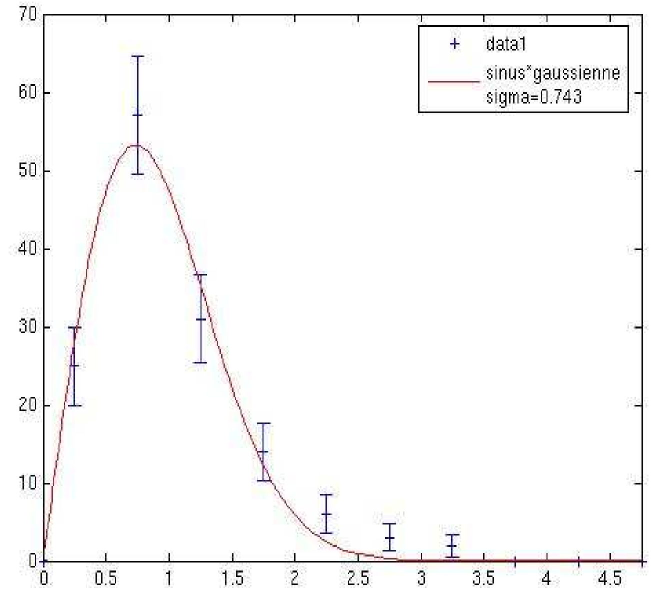
(using Solar bursts)



Principle of the triangulation



Reconstructed directions versus sun ephemerids

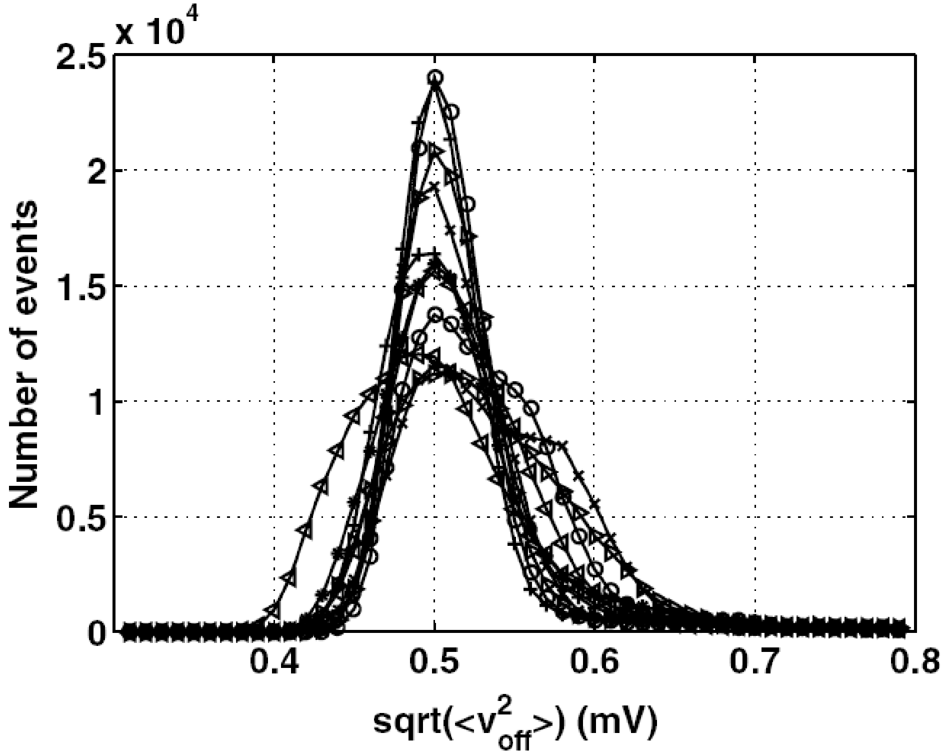


Distribution of the Residues

Direction accuracy

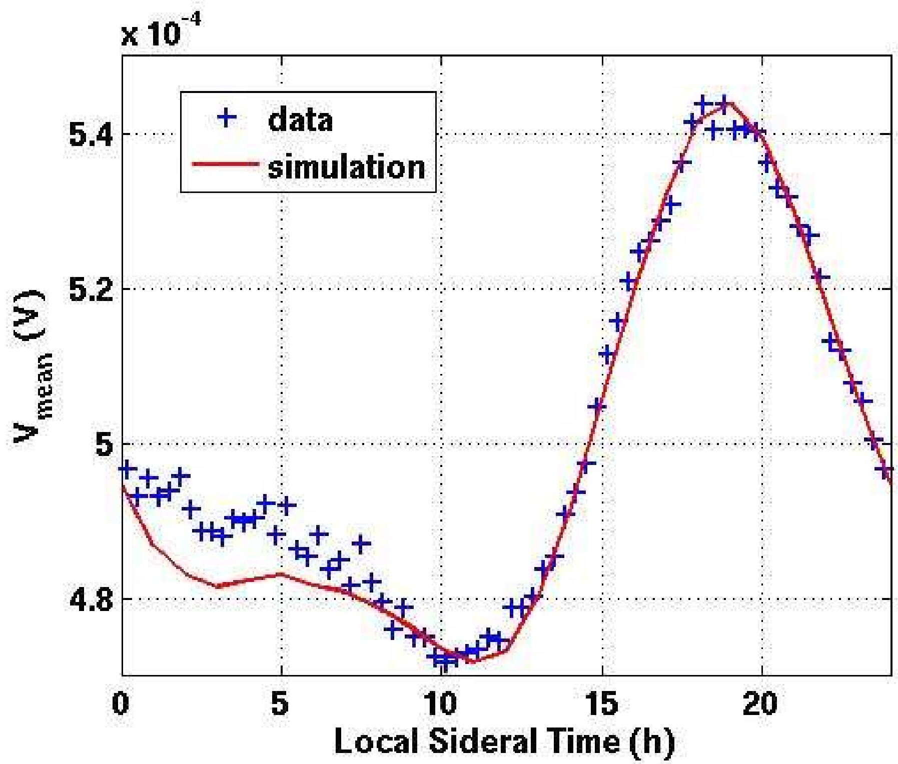
σ = 0.74 °

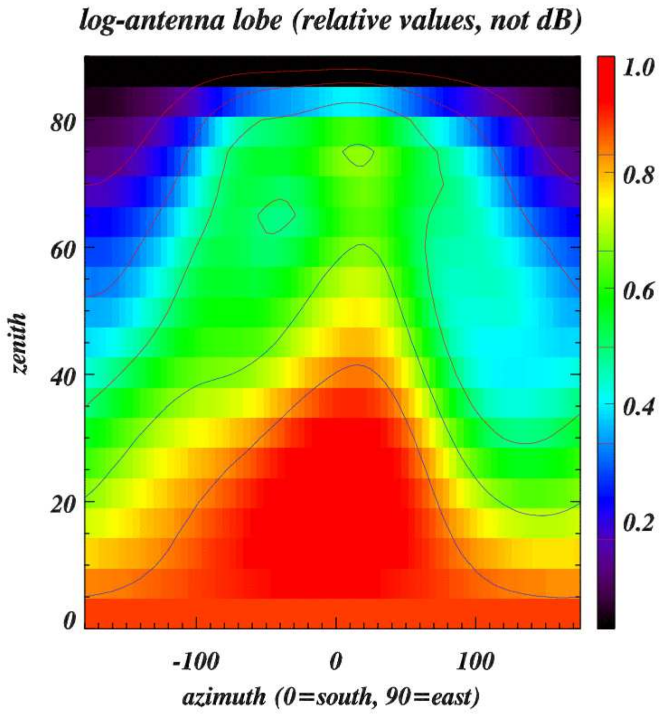
Signal sensibility



Distributions of the ground floor signal in the 40-70 MHz band after cross calibration of the antennas gains

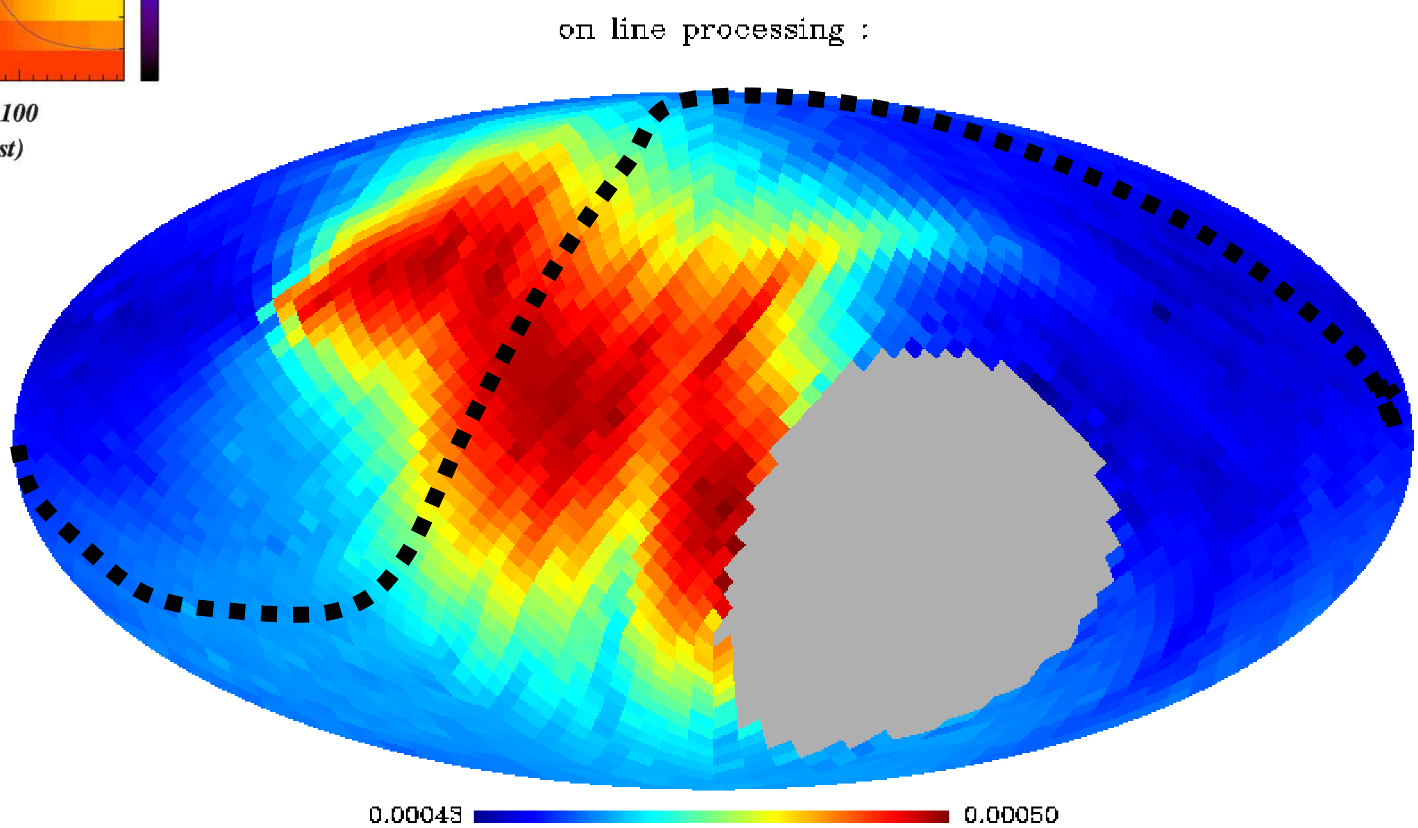
Time evolution of the mean ground floor
compared to
the galatic + Cas.A simulated contributions seen through 45° lobe antennas





Sky Coverage

from recorded radio events (chance & EAS coincidences)



CODALEMA EAS Results

Radiodetection capabilities with CODALEMA

• **Trigger capabilities :**
(1 ant. + narrow band)

• **Shower direction : triangulation**
(several ant. + time tagging)

• **field topology: extend & core location**
(several ant. + field distribution on the ground)

• **Primary particle energy : $\propto$ total charge $\propto$ electric field**
(amplitude of the signal)

• **Nature : longitudinal profile, X_{max}**
(shape of the signal)

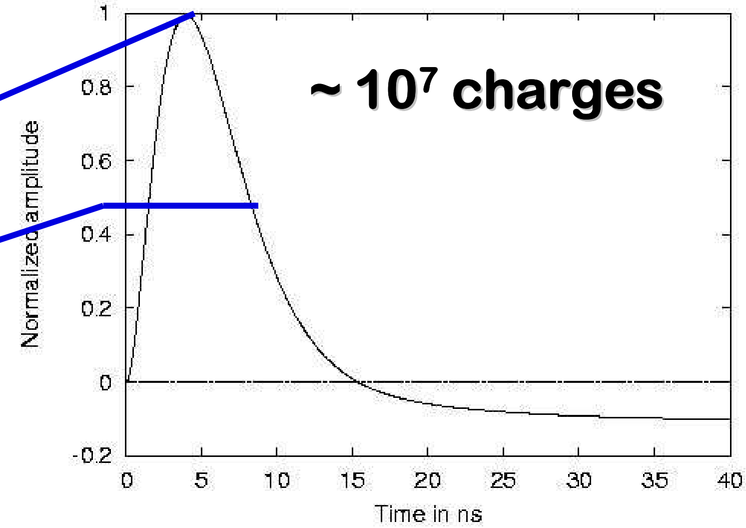
To demonstrate yet

Expected Signal @ 10^{17} eV

With Vertical shower @ small impact parameter @ Nançay

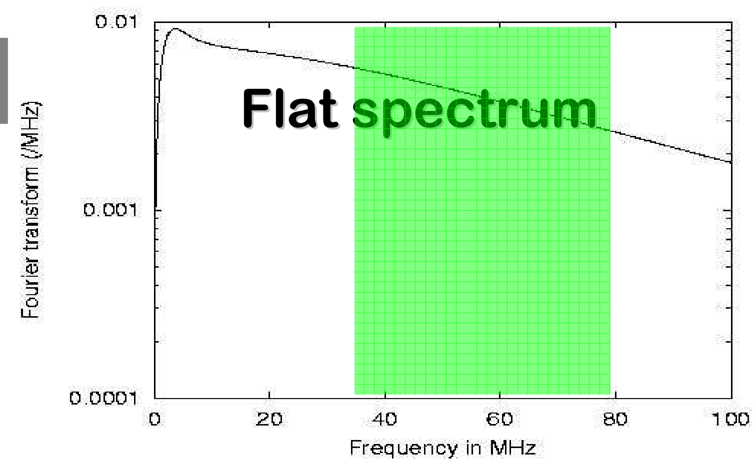
Following H. R. Allan (1971) Signal simulation:

ε_{pk}~150 μV/m
FWHM duration ~ 8 ns



- **Narrow-band antennas**
- **Small antenna array**

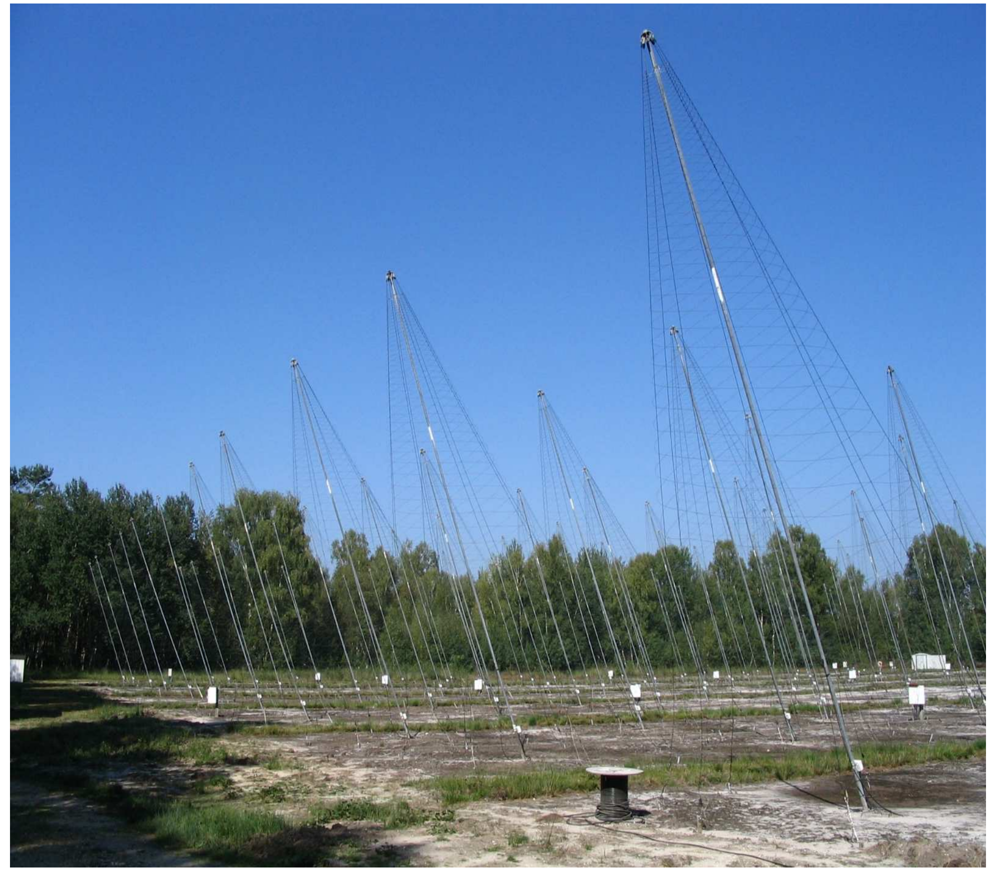
Our current setting @ Nançay



CODALEMA 2004-05 with spiral Ant.

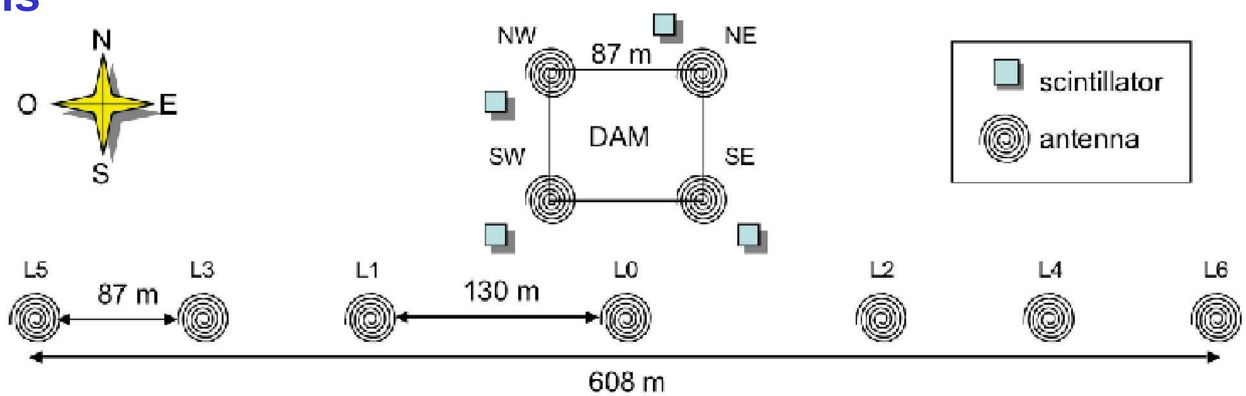
DAM: (Decametric Array) of the radio observatory of Nançay

- spiral log periodic ant., 1-100 MHz (3Db), 90°Lobe, circular pol.
- FILTERED IN 24-80 MHz
- Waveform 8 bits, 500 MS/s, 10 μs



TRIGGER: 4 Stations of Scintillators (2 m^2) in coincidences

- Signal recording + Time of fly analysis
- => Reconstruction of the shower directions

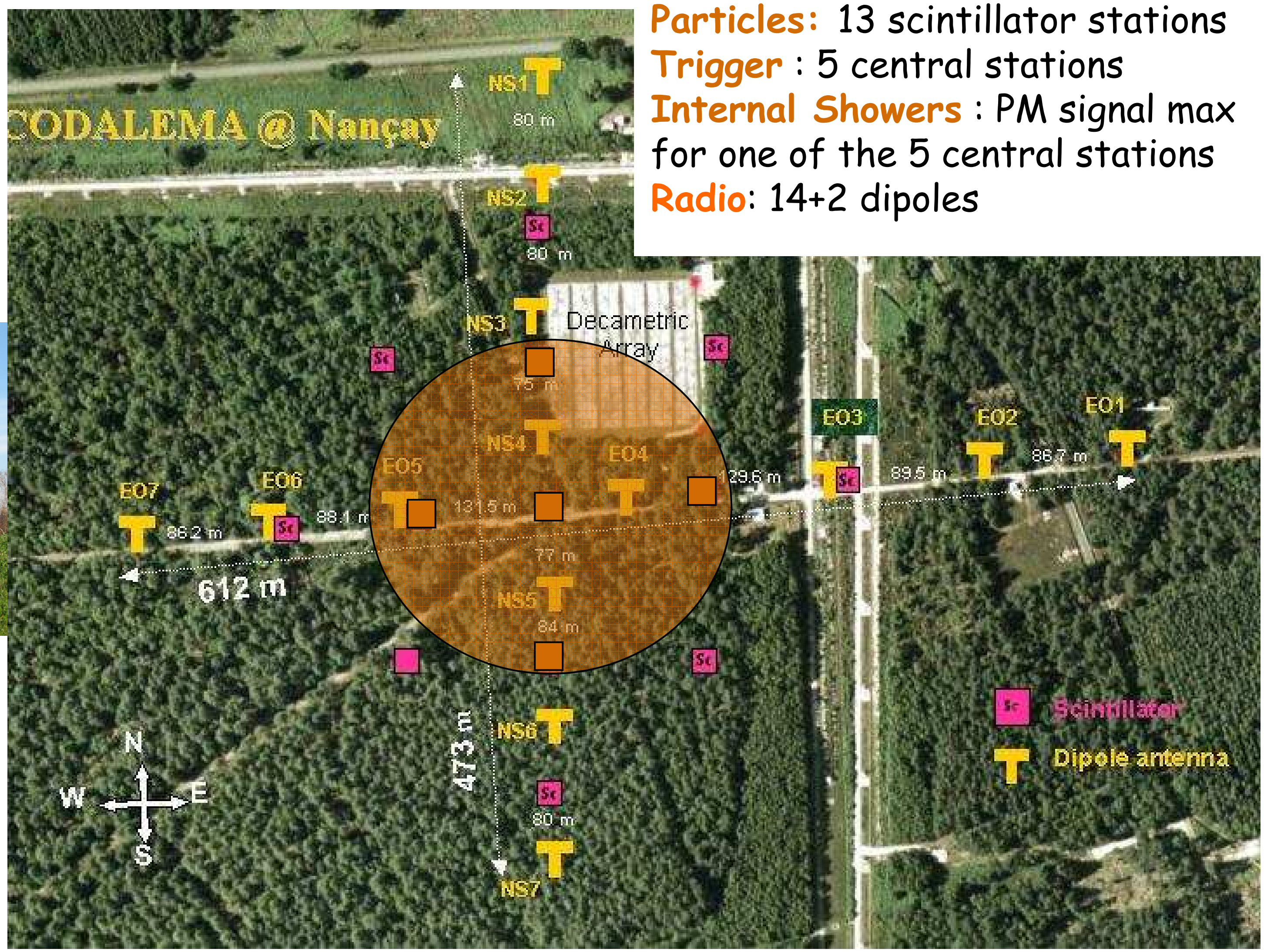


CODALEMA 2007 setup with dipoles

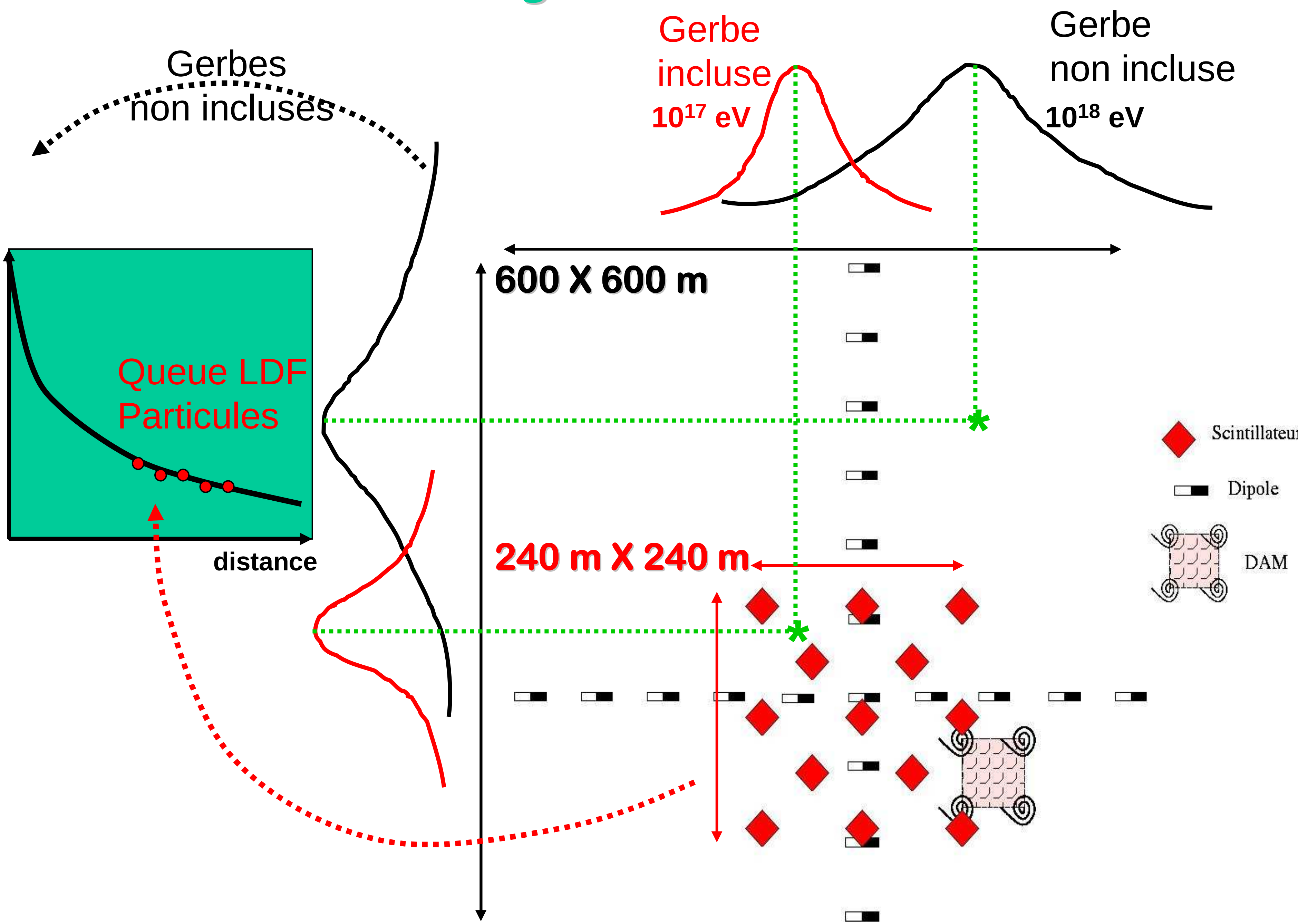
Particles: 13 scintillator stations
Trigger : 5 central stations
Internal Showers : PM signal max for one of the 5 central stations
Radio: 14+2 dipoles

Scintillator array

Dipole Array
1-200 MHz
12 bit ADC

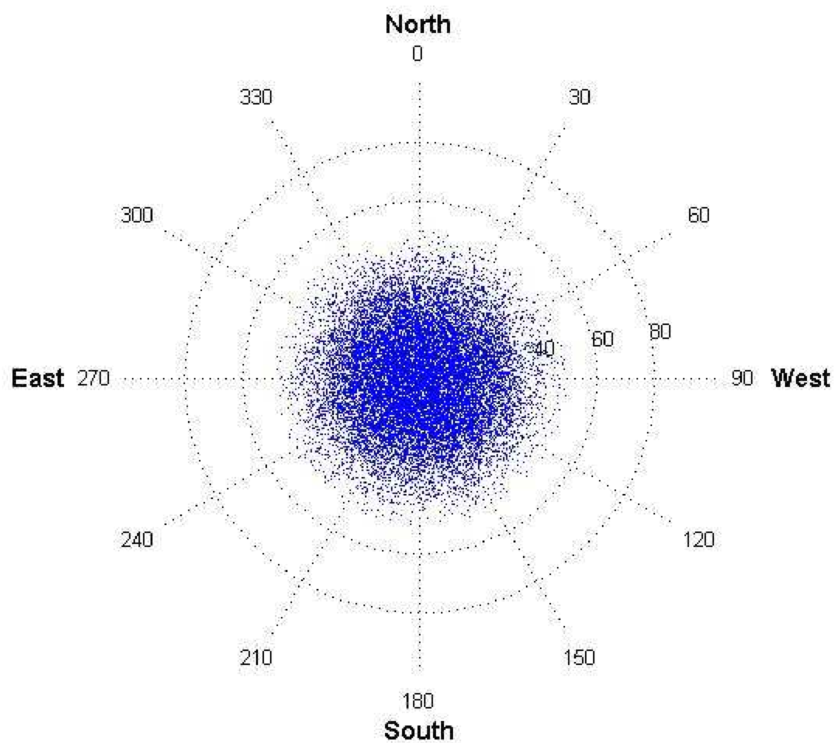


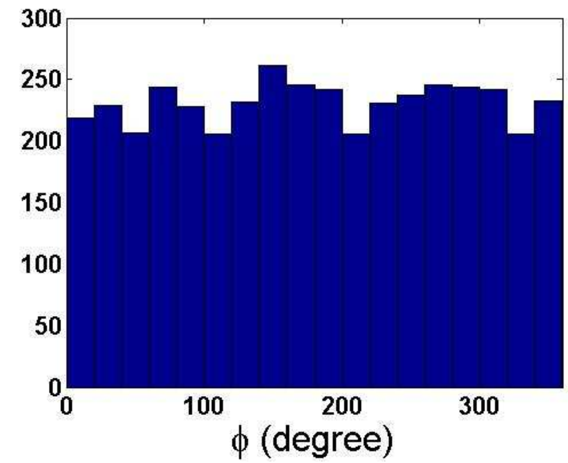
Etalonnage Particules-Radio



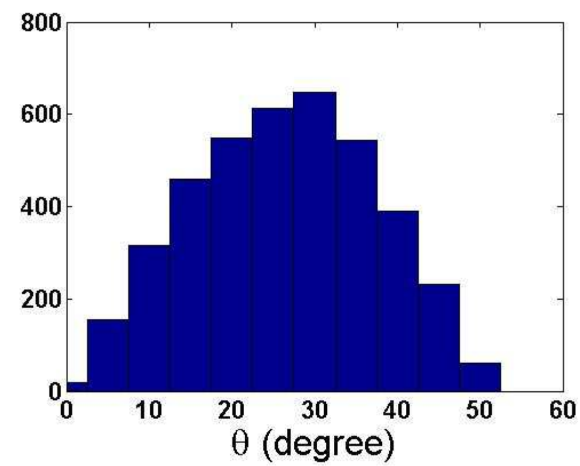
Scintillator distributions (internal)

Shower arrival direction calculated with the scintillator data





Azimuthal distribution



Zenithal distribution
Limited at $\theta < 50°$

Shower energy deduced from scintillator data (CIC method, precision 30 %)

=> Energy threshold ~ 10^{15} eV

Statistic 2007

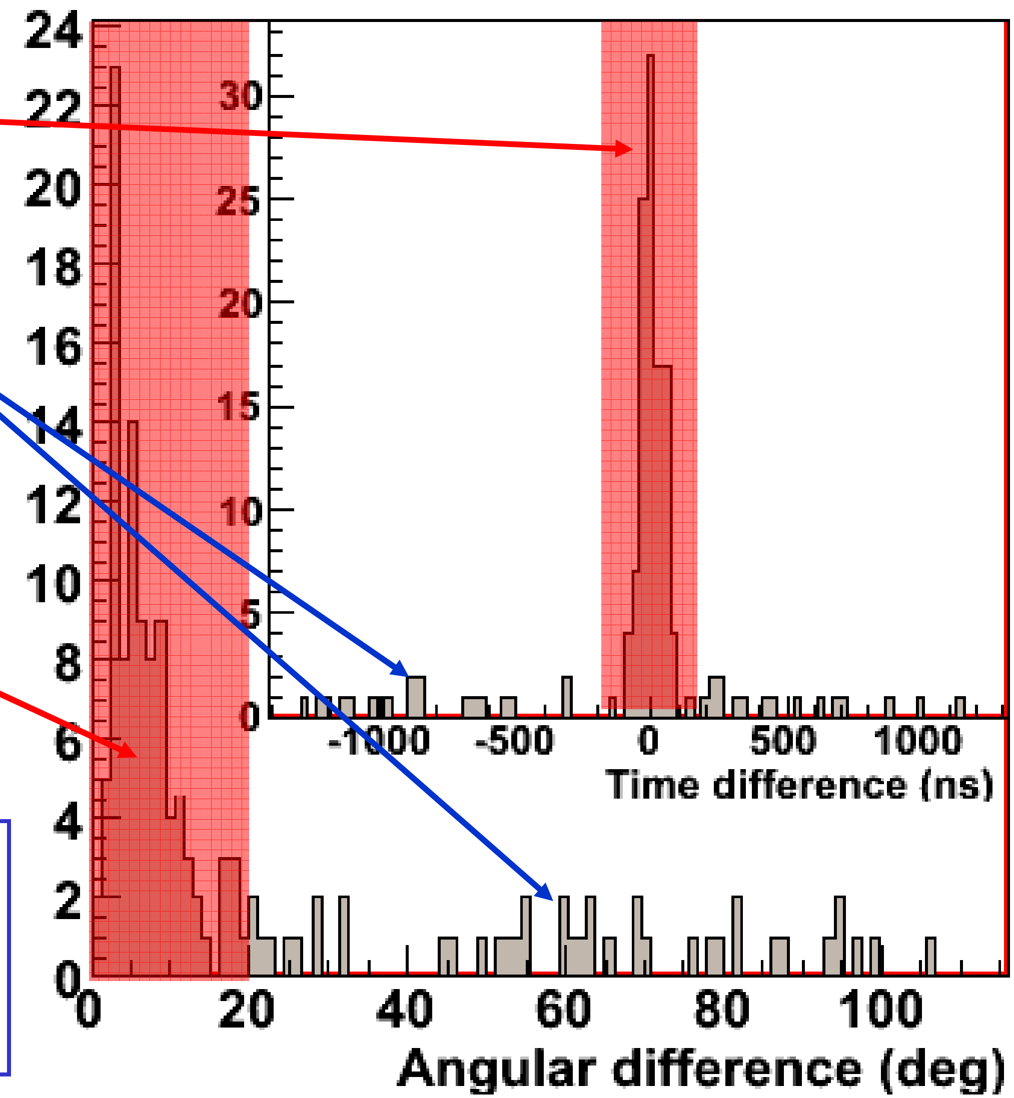
Effective time (since december 2006)	170 days
Number of trigger (5 central stations) (Counting rate= 1 evt/day)	33 795
With internal events (Energy Known)	18 354
With Radio coincidences (>= 3 antennas tagged)	613
....+ Δtime < 200ns + Δang.< 20°	141 (Counting rate=0.83 evts/day)
....+ Energy Known	43

Radio-particles time & Arrival direction coincidences (for ≥ 3 antennas flagged)

Sharp peak (< 100ns)
= EAS candidates

Flat distribution
= fortuitous events

sin(Δα).Gaussian
=> σ = 4°



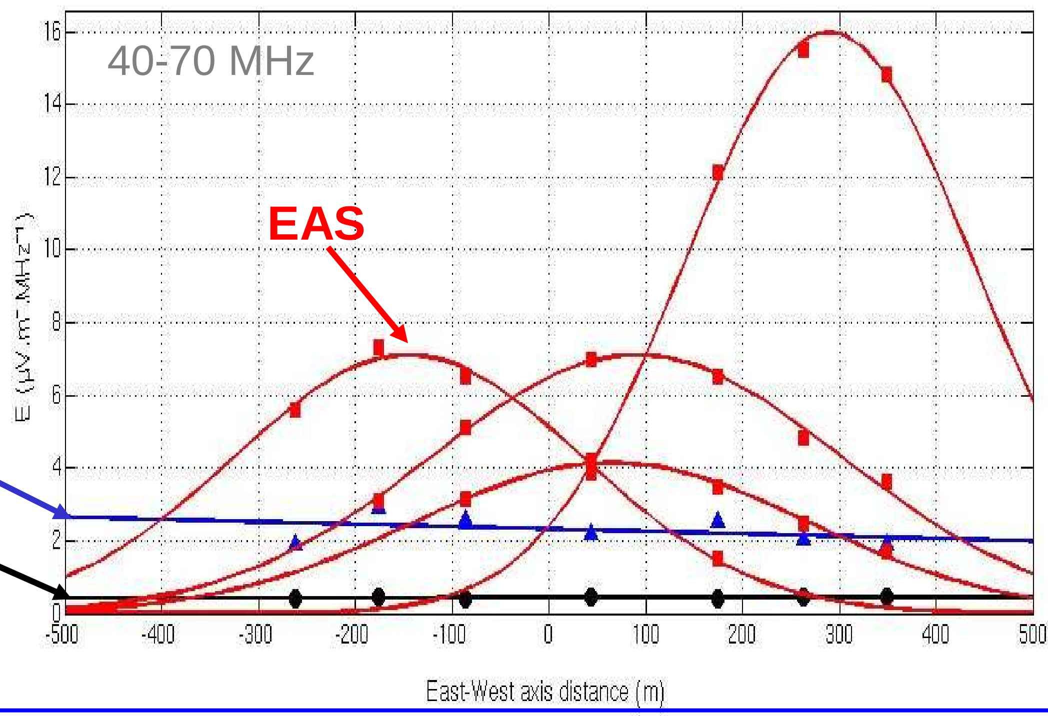
Reconstruction of EAS arrival directions is proved via Radio-Detection

"Antennas" direction – "Particles" direction

Electric Field topologies

Variable antenna multiplicity (limited array)

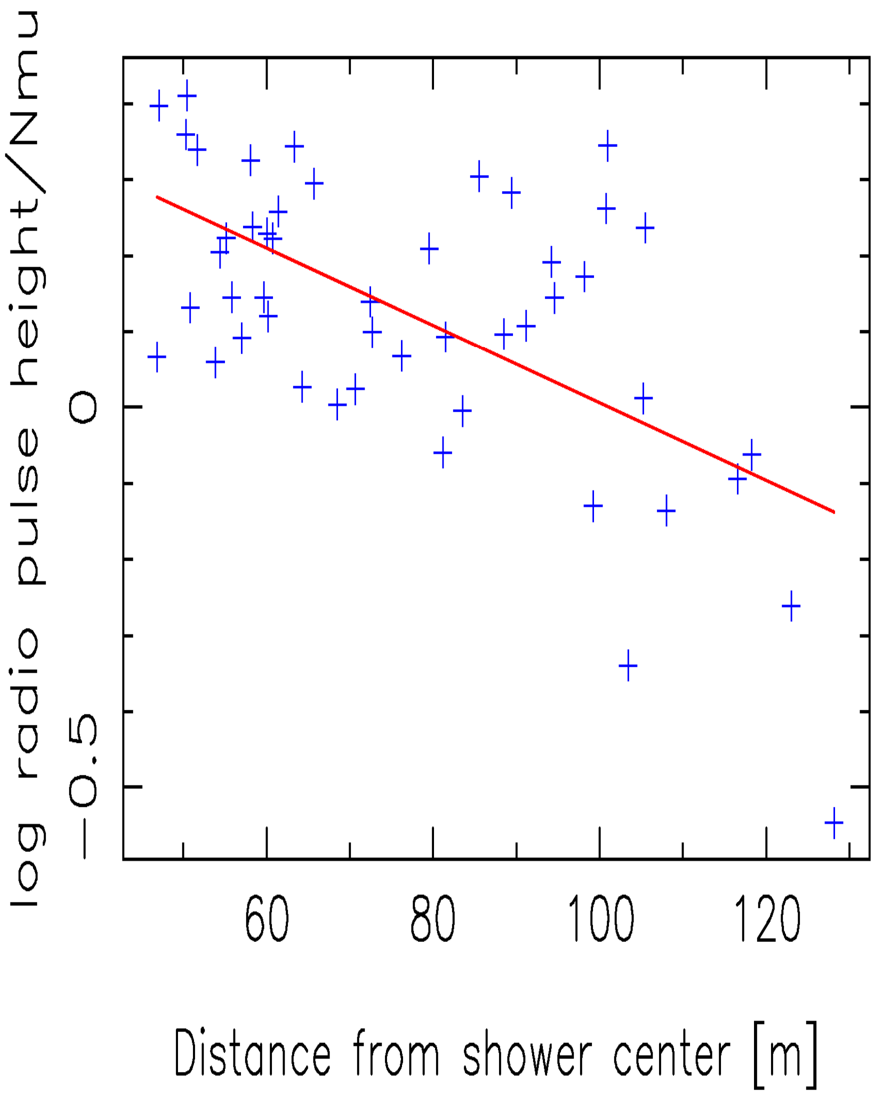
The entire shower development is seen by every antenna

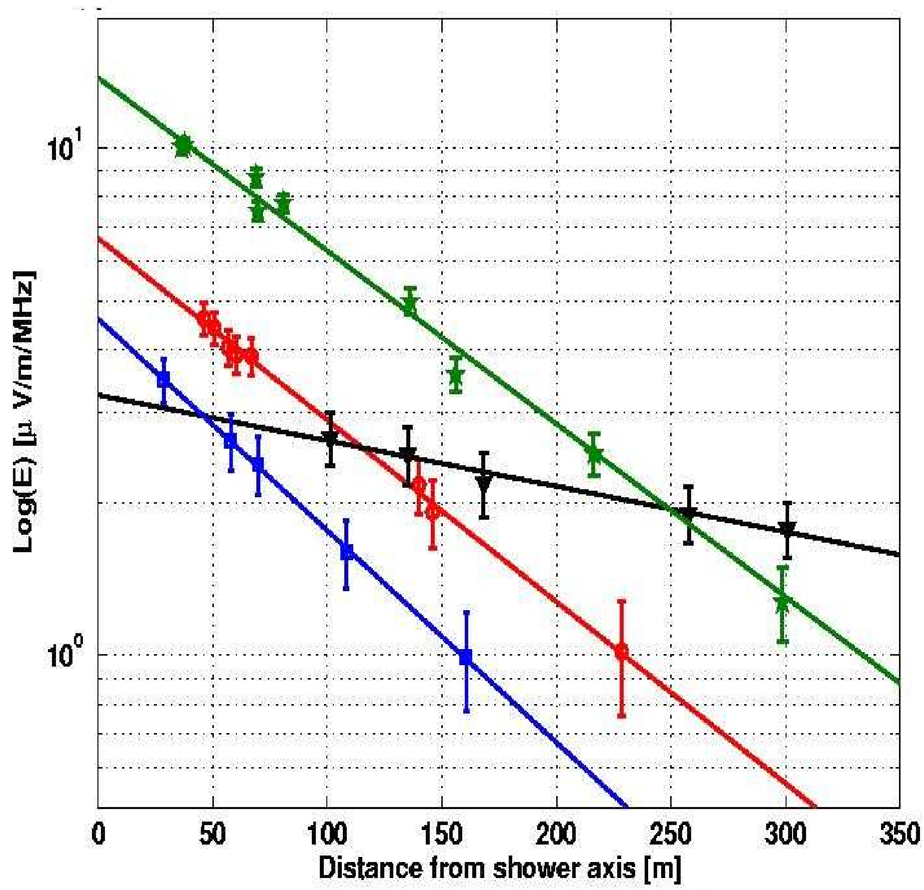


Free of particle ground density fluctuations

Field topology is a desive criterion of selection in stand alone mode

Shower reconstruction

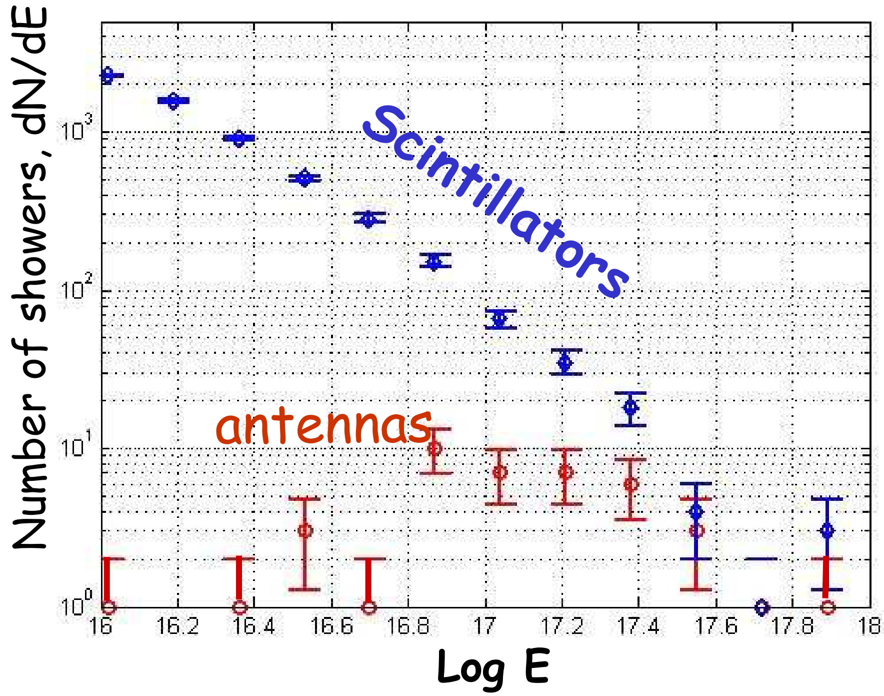




Field Measurements

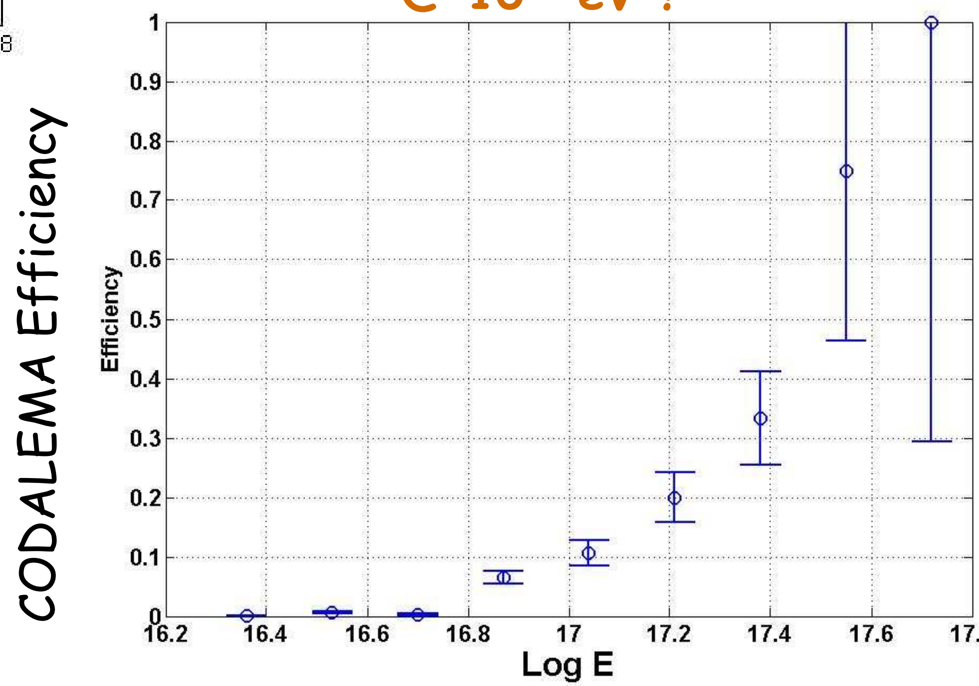
Up to 600 m @ ~ 10^{17} eV

Energy distribution & efficiency of radio



Histogram not corrected for the acceptance

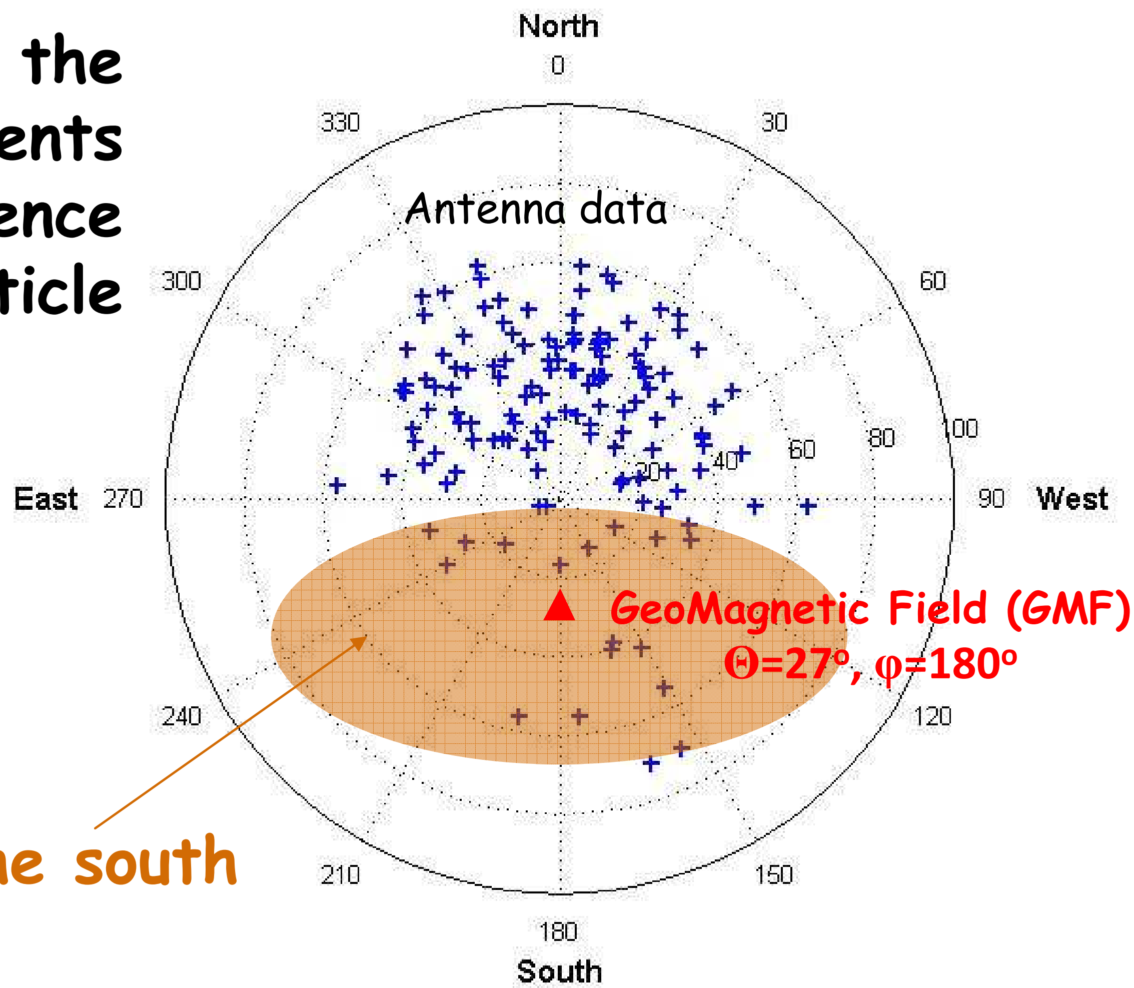
Full efficiency reached @ 10^{18} eV ?



=> But detection efficiency depend on the measured polarisation?

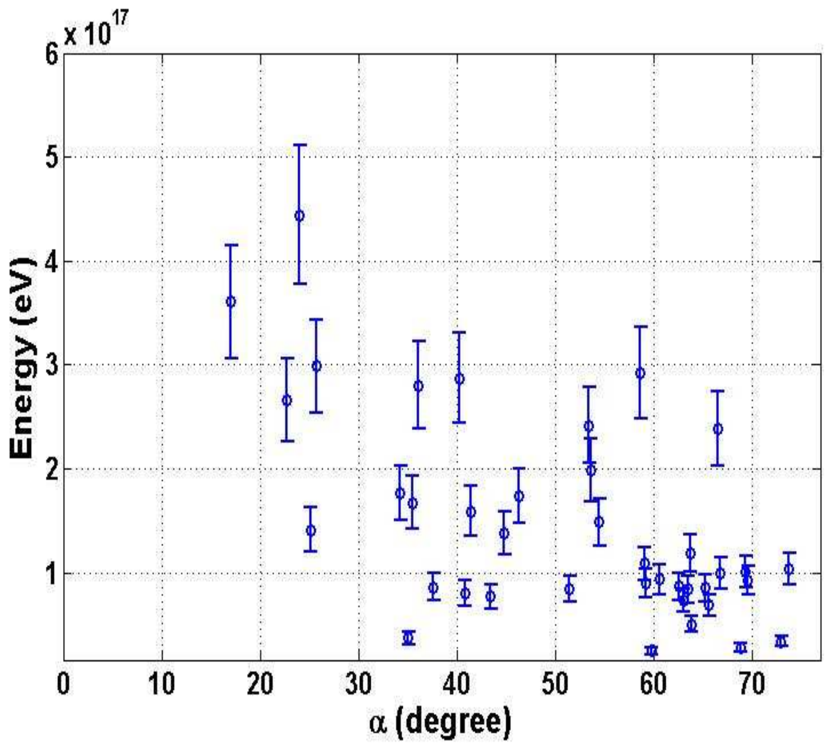
Shower arrival directions

Arrival directions of the 141 radio events detected in coincidence with the particle detector array



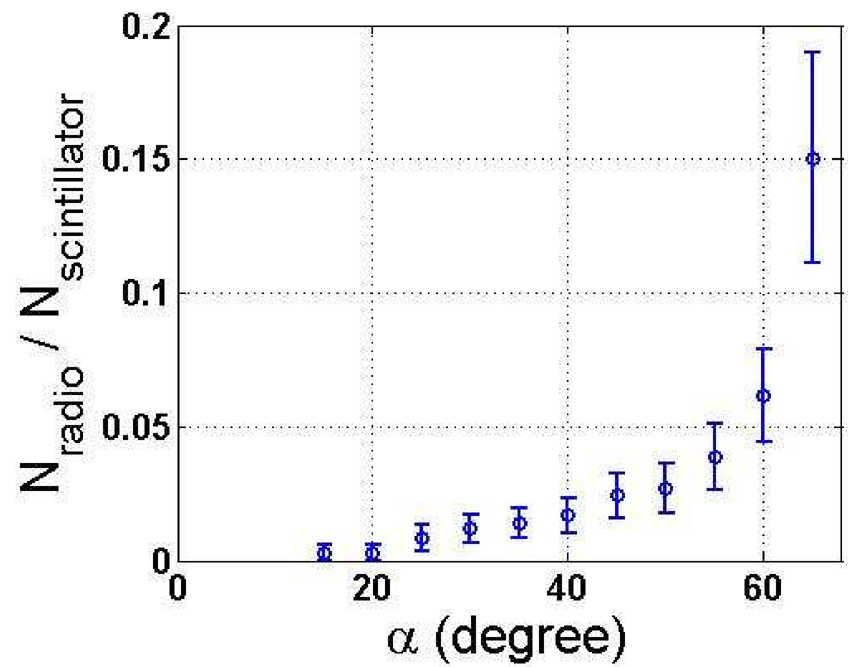
Shower deficit in the south Direction !!

Showers arrival directions / Energy



For the 41 « radio + internal showers » with known energies (30% accuracy with CIC method)

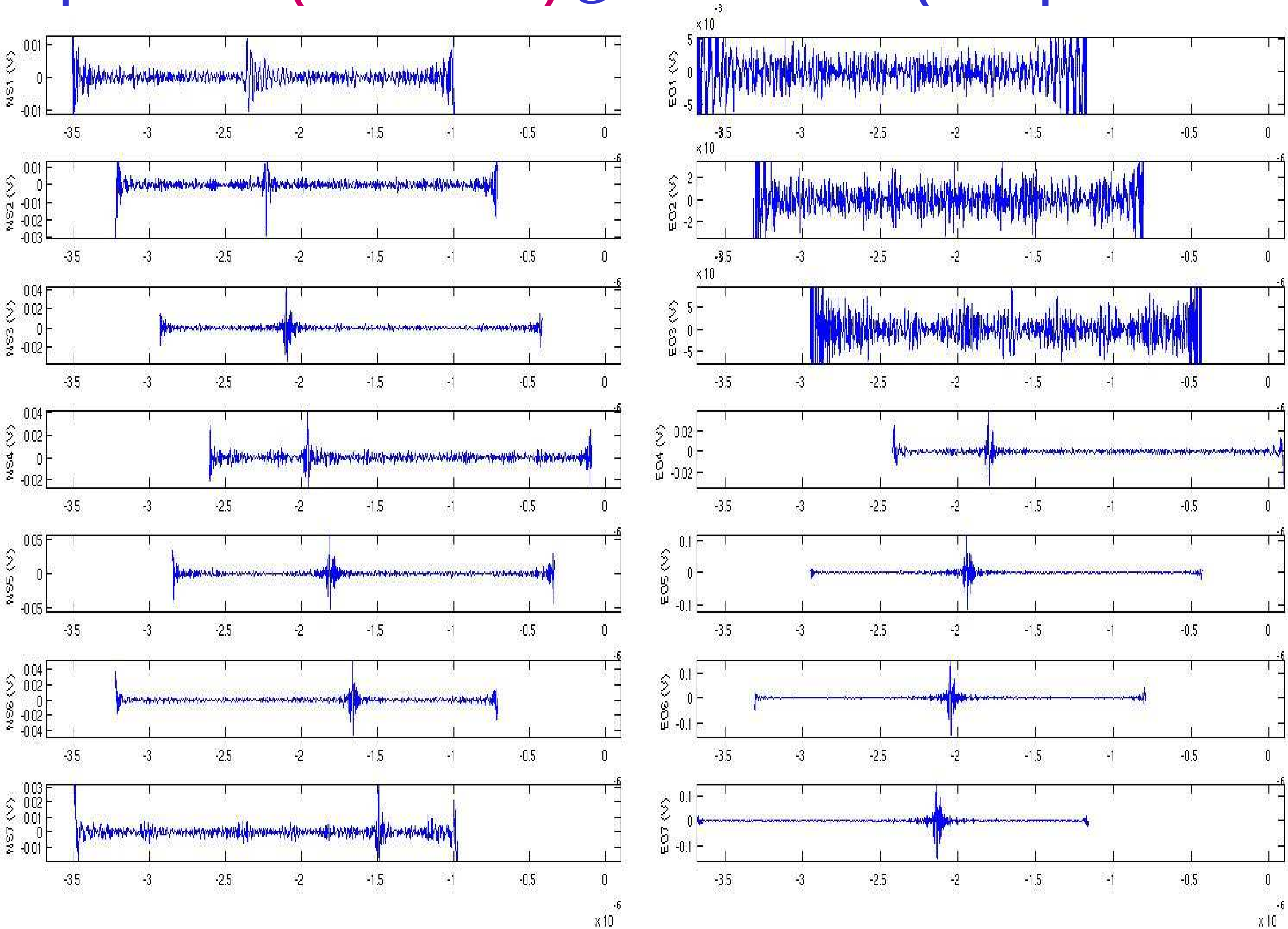
α : angle between GMF and cosmic ray arrival direction



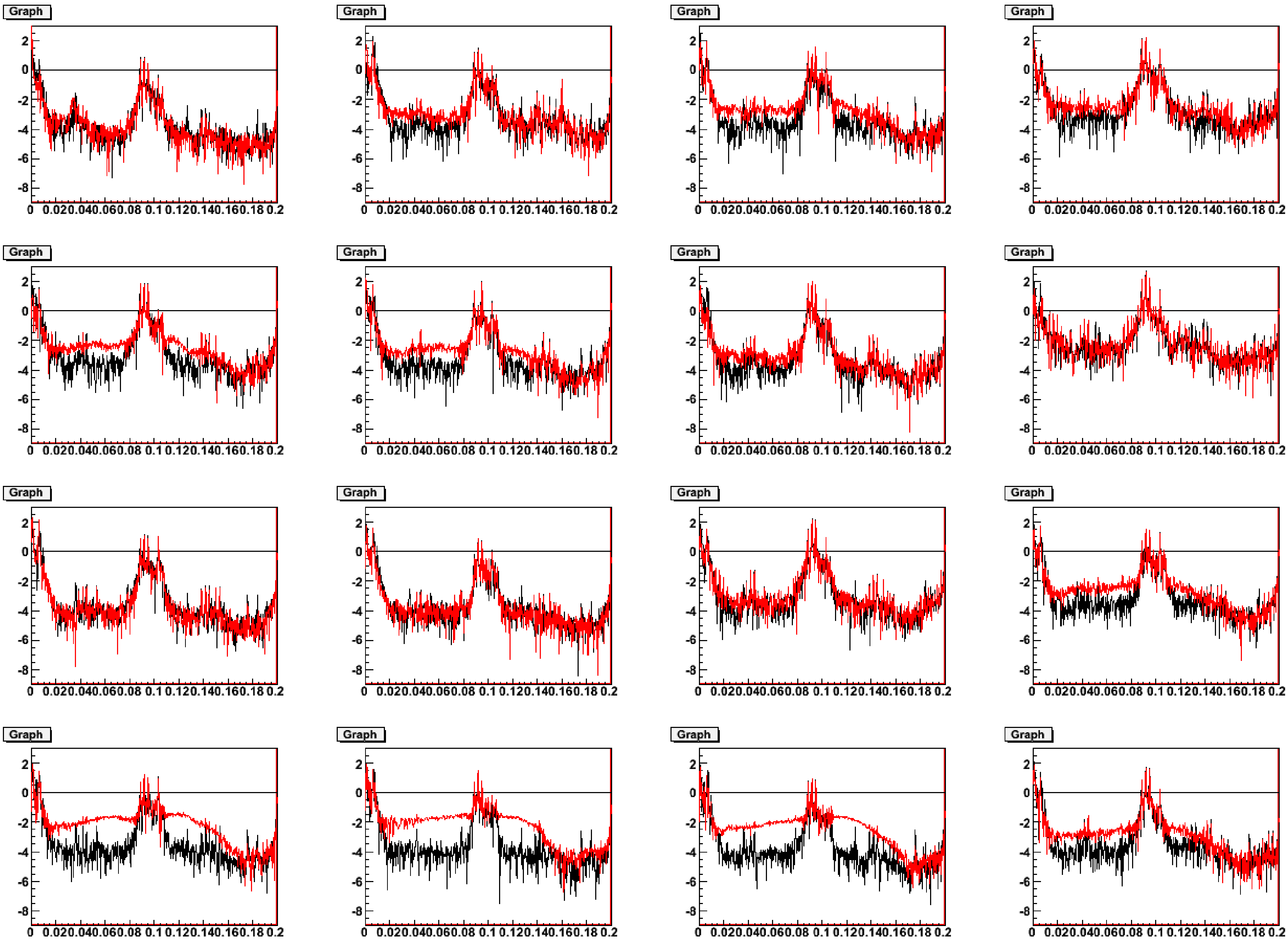
Evidence for a geomagnetic effect in the radio emission process ?

=>Strong constraints on the emission process model ?
=>Impose Full-polarisation detection ?

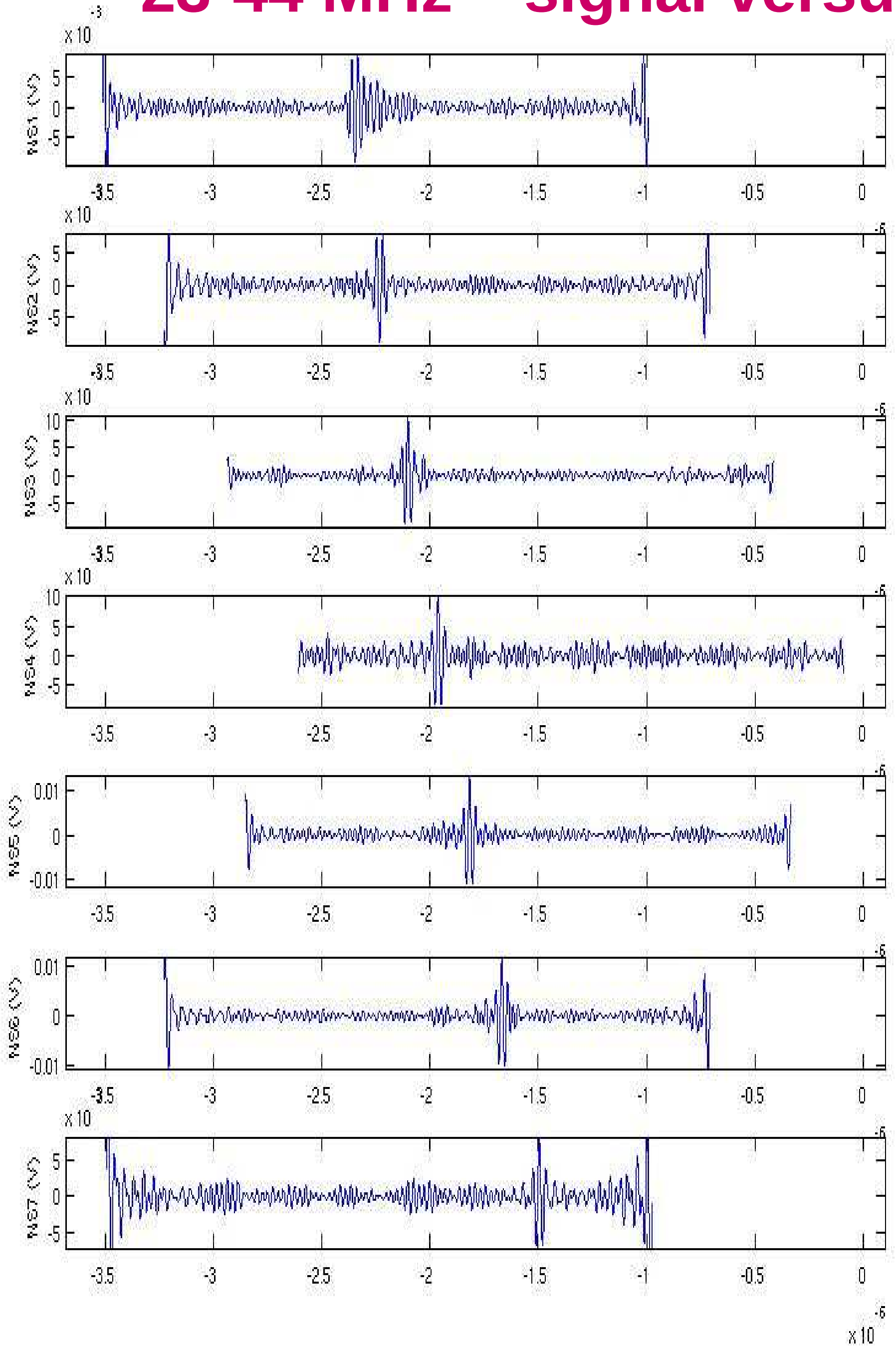
Dipôle event (23-130 MHz) @ E~2.5 10^{18} eV (from particle Det.)

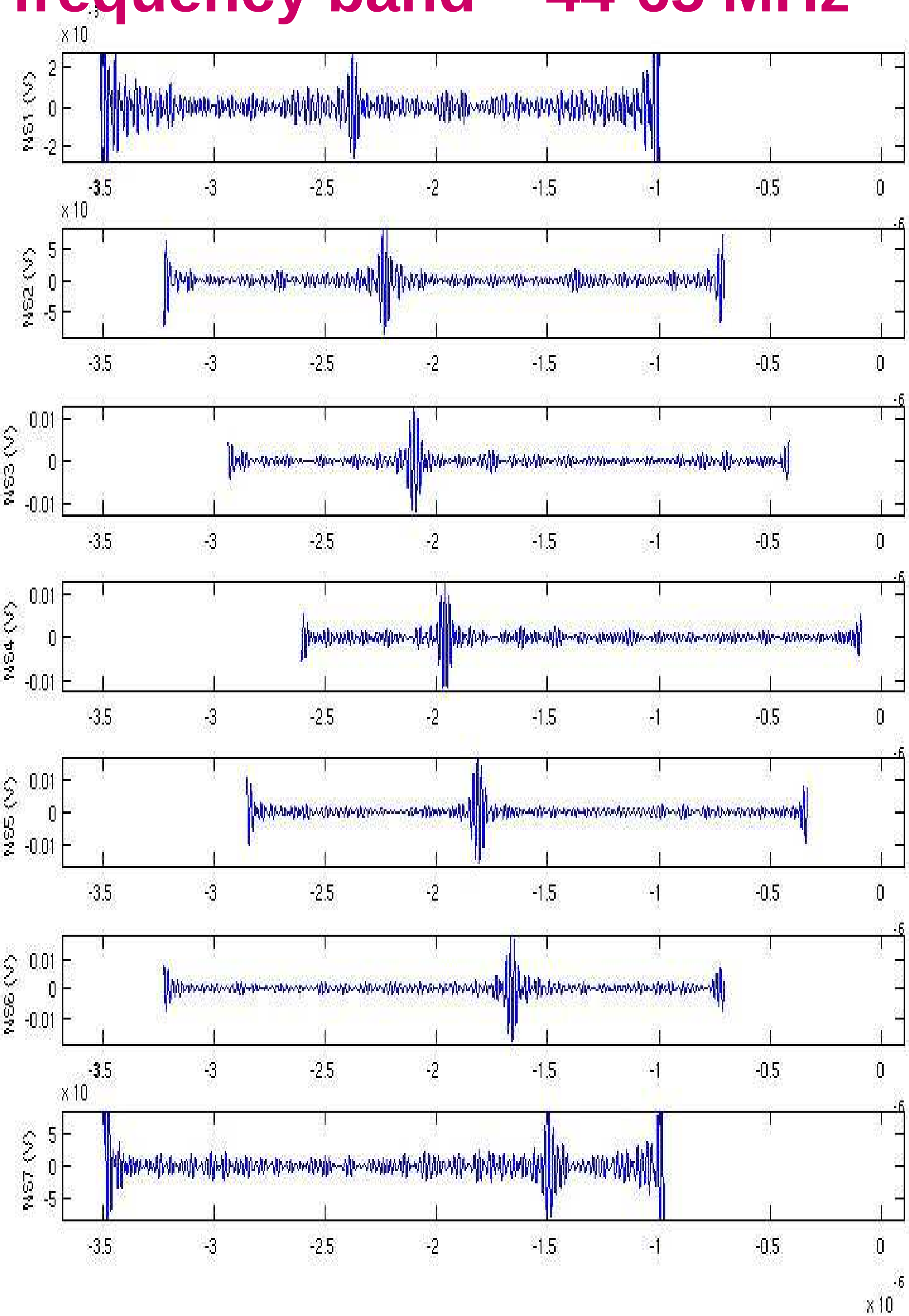


Frequency spectrum

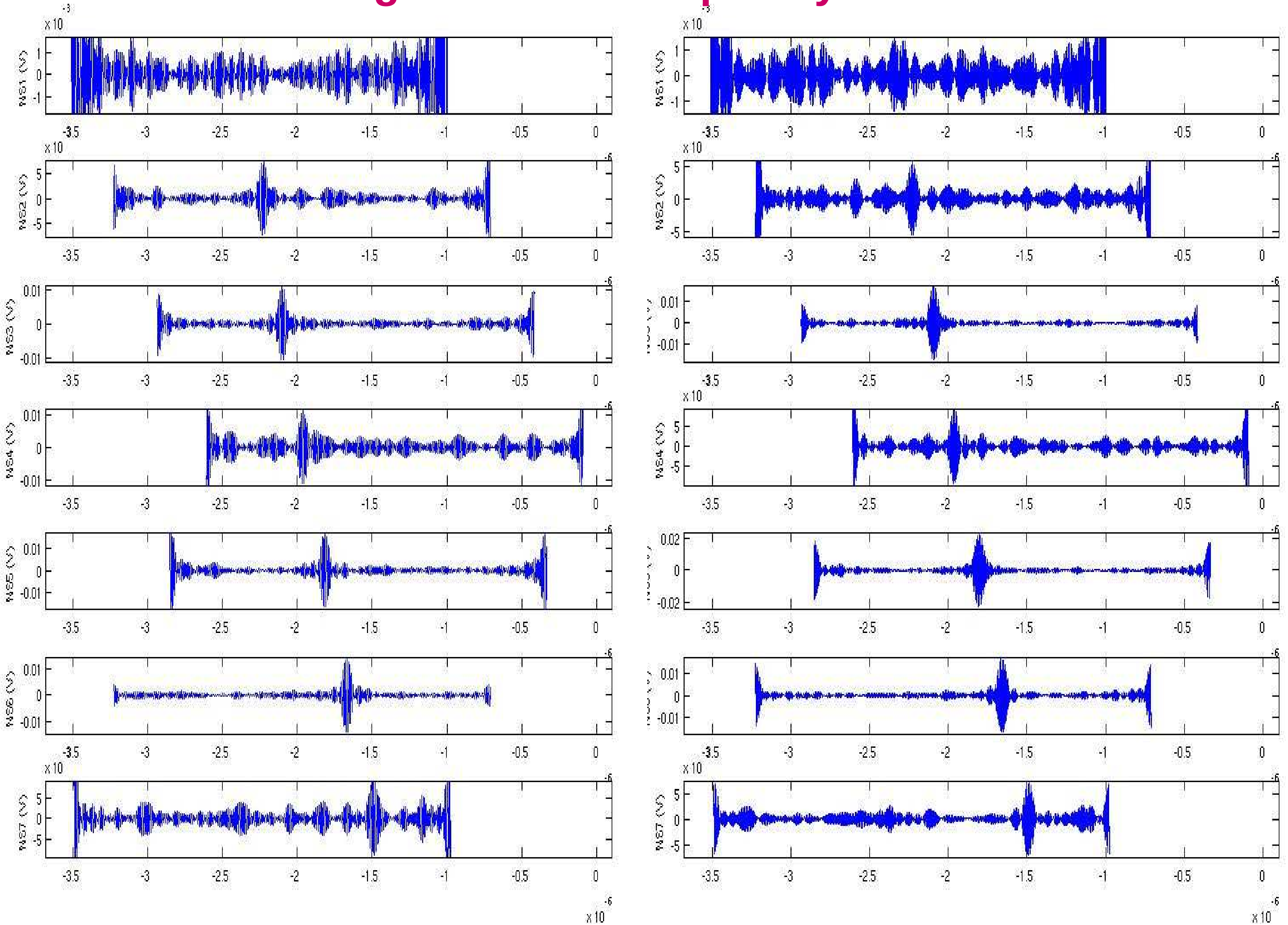


23-44 MHz signal versus frequency band 44-65 MHz

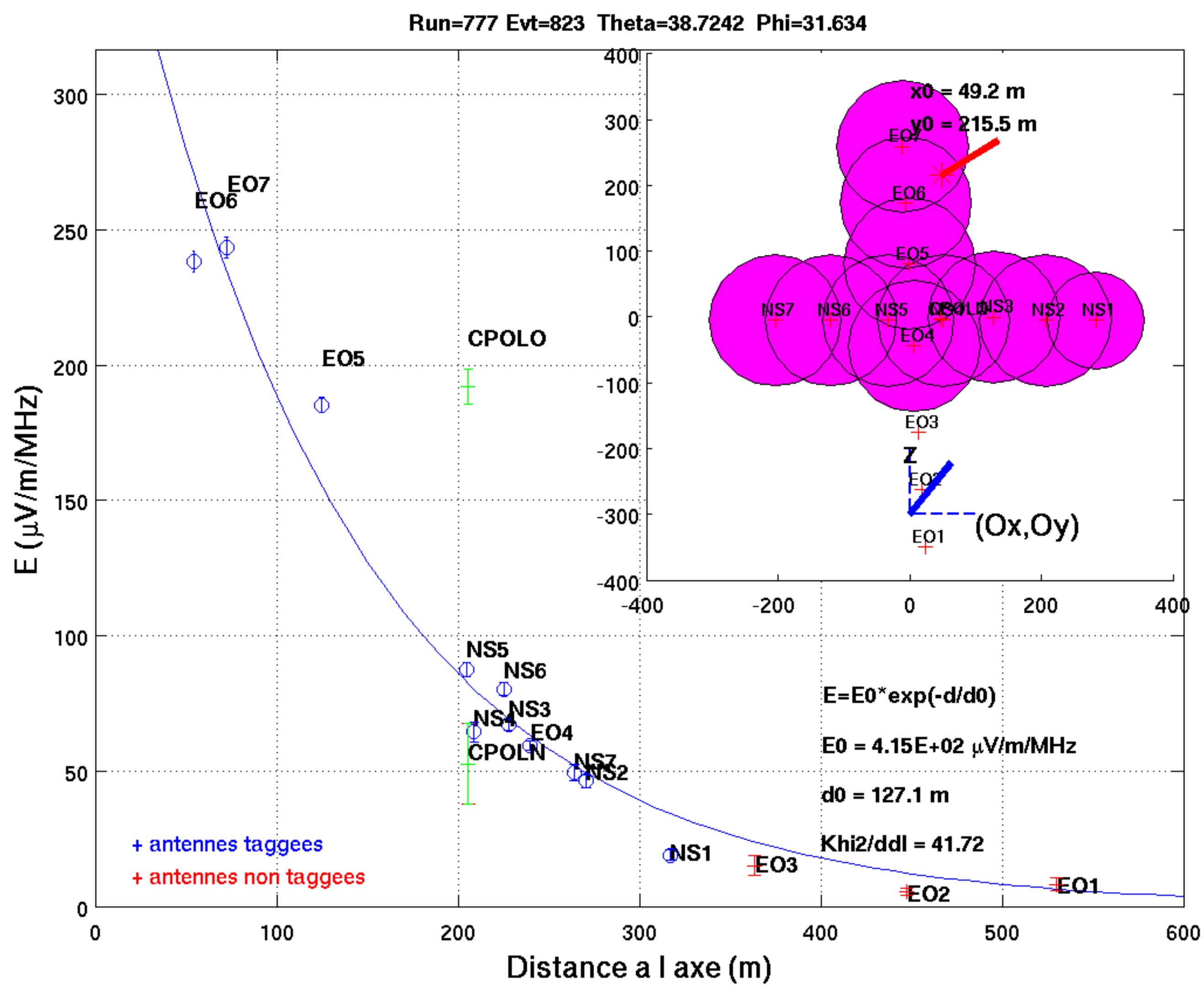


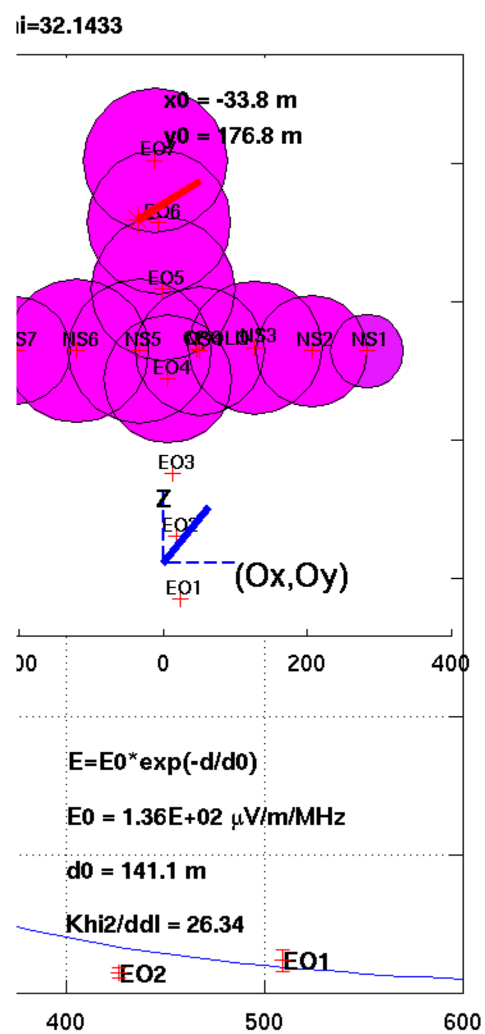


65-86 MHz signal versus frequency band 109-130 MHz

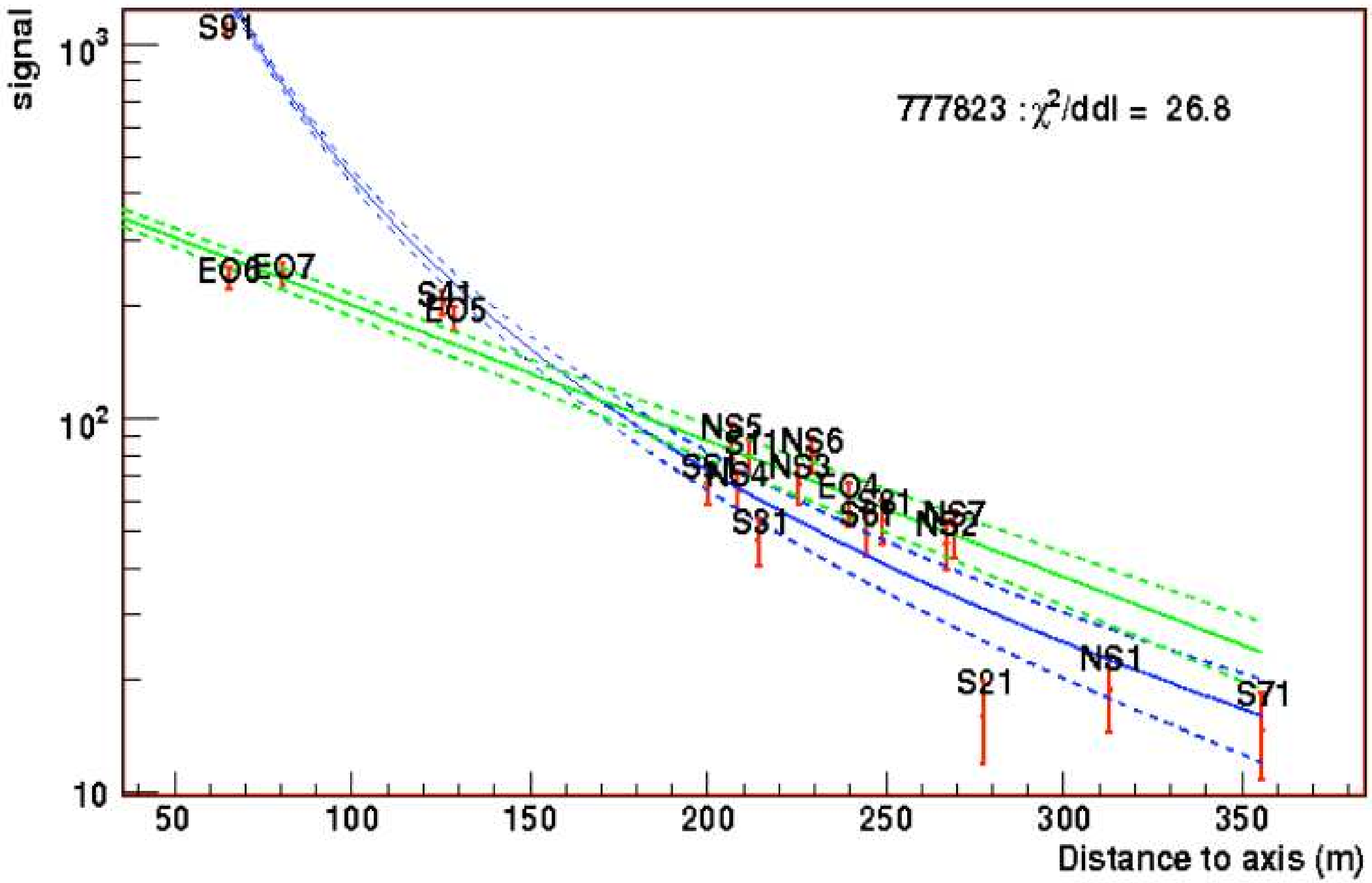


Influence de la fréquence sur les informations physiques ?





Analyse hybride
LDF Particules – LDF Radio



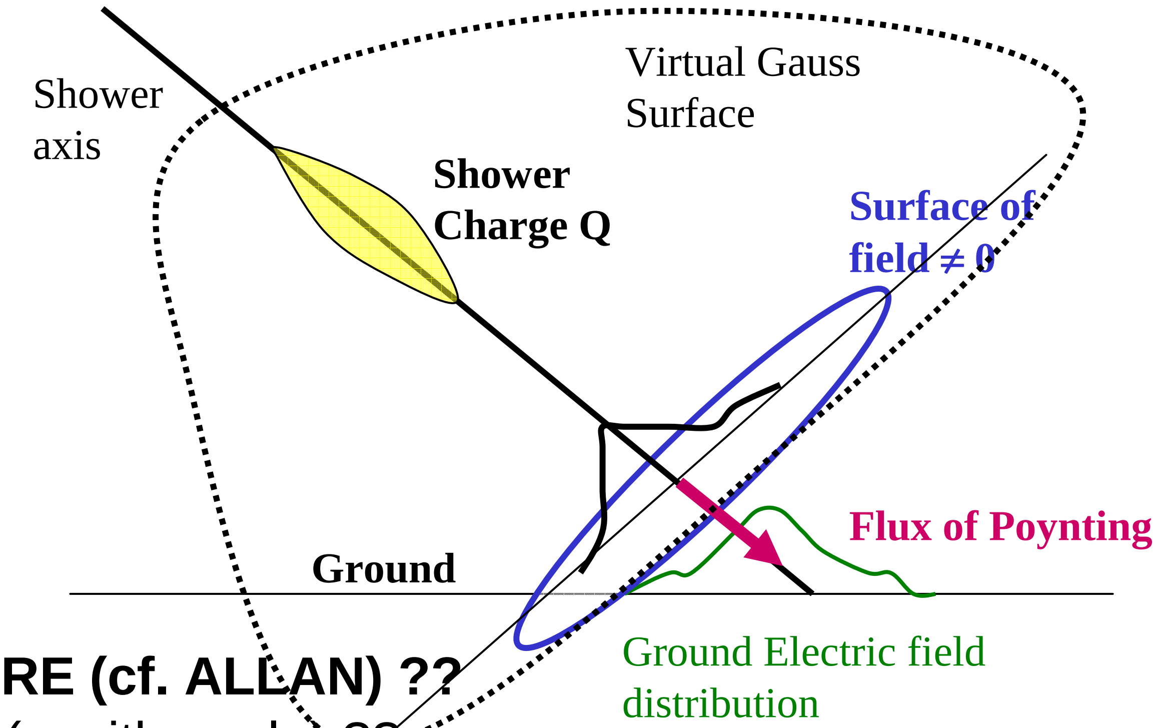
Tentative of energy estimation (1)

(via the global features of the EAS)

In the shower frame:

$E(d) = E_0 . \exp(-d/d_0)$

γ: geomagnetic angle with the shower



ELECTRIC FIELD at the CORE (cf. ALLAN) ??

=> $E_{primary} \sim E_0 . \sin(\gamma) . \cos(\text{zenith angle})$??

GAUSS FLUX (charge excess…) ??

=> $E_{Primary} \sim Q / \varepsilon = \int E(d) . dS = E_0 . d_0^2$??

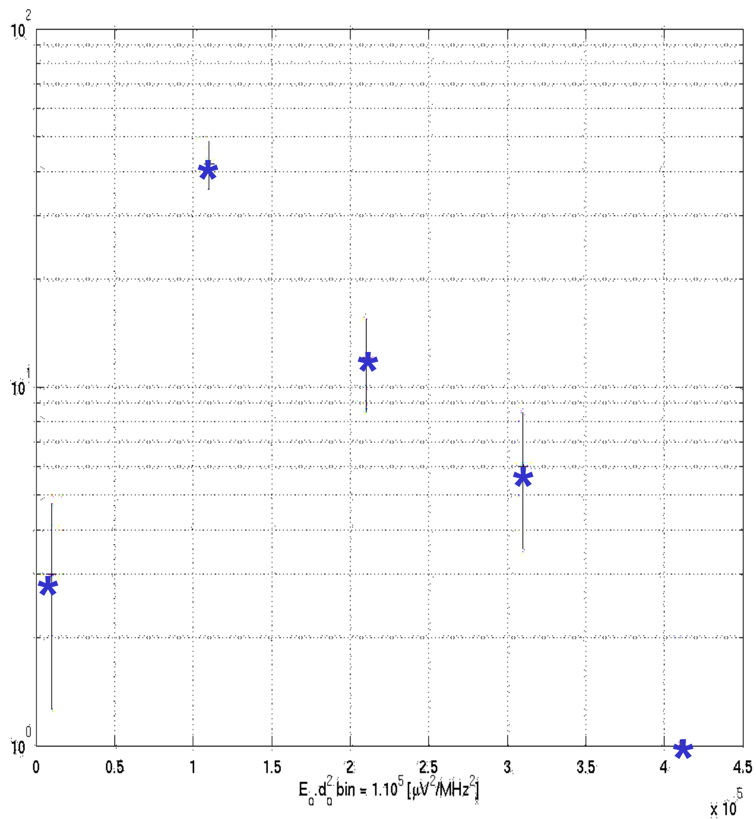
RADIATED ENERGY (geosynchrotron,…Poynting) ??

$\Rightarrow E_{primary} \sim \int P . dS = E_0^2 . d_0^2 / \sin^2(\gamma)$??

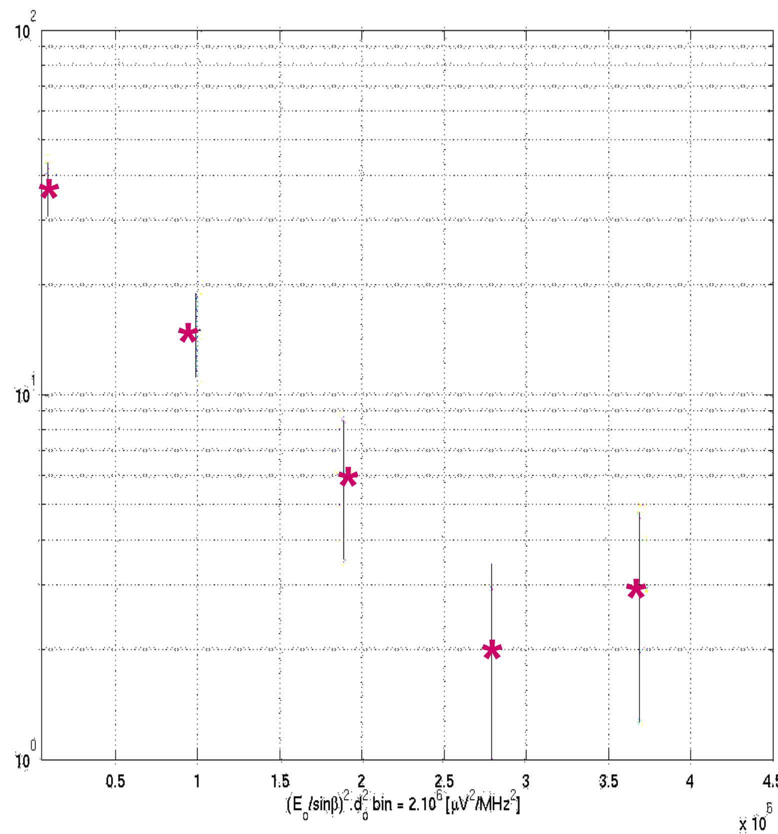
Tentative of energy estimation (2)

(very preliminary)

$E_0 . d_0^2$ **spectrum (a.u.)**



$E_0^2 . d_0^2 / \sin^2(\gamma)$ **spectrum (a.u.)**

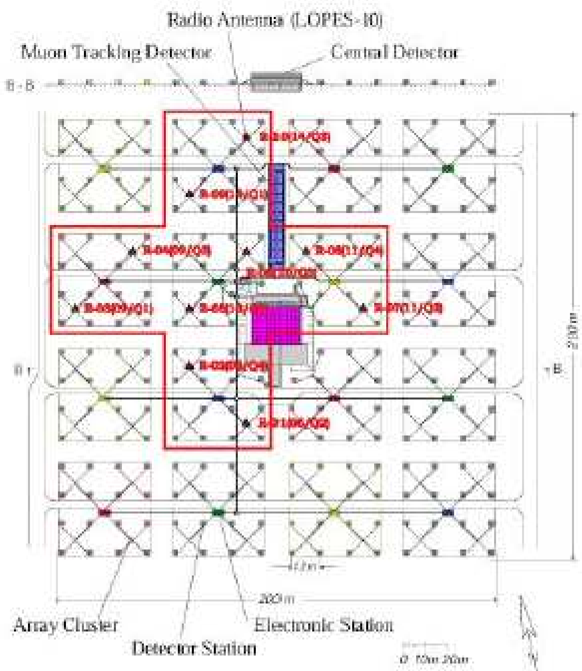


At present time: no clear correlation of E_{radio} vs $E_{particles}$

=> Need more statistics

LOPES EAS results

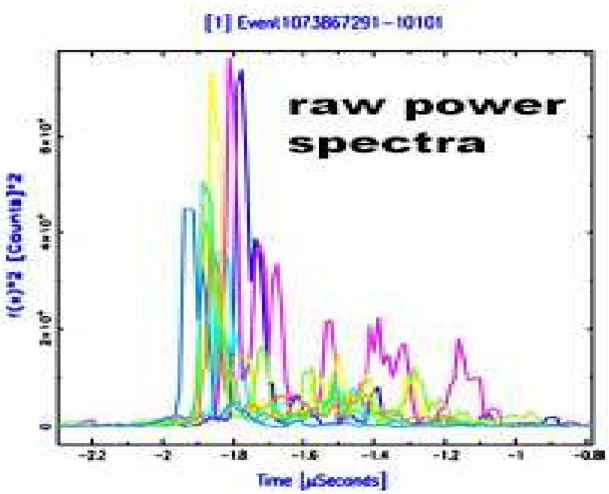
LOPES



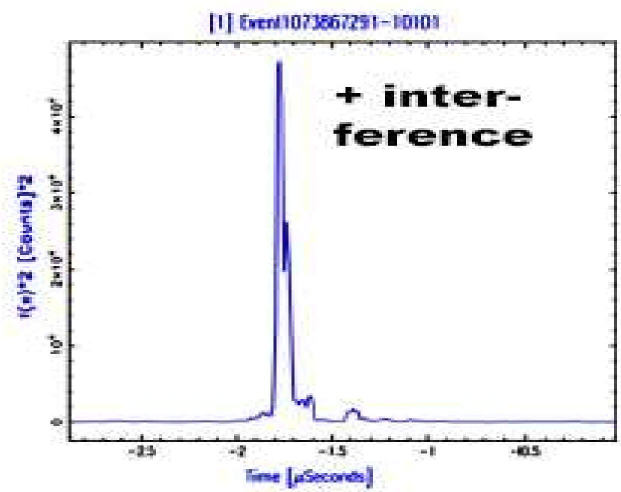
10 LOFAR antennas

Trigger KASCADE

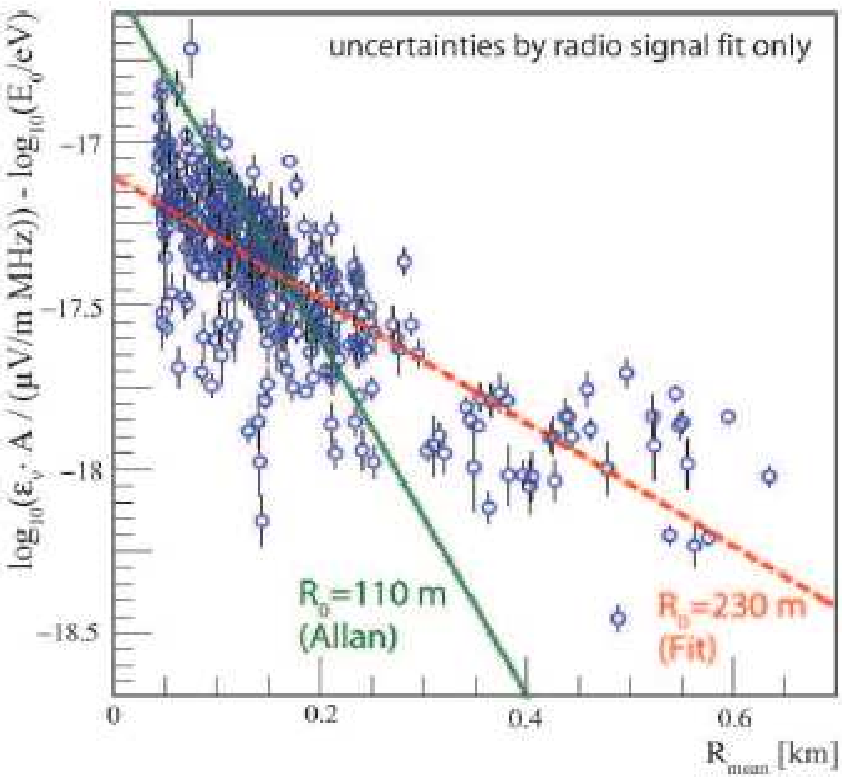
Bandwidth: 40-80 MHz + Sampling: 80 MS/s



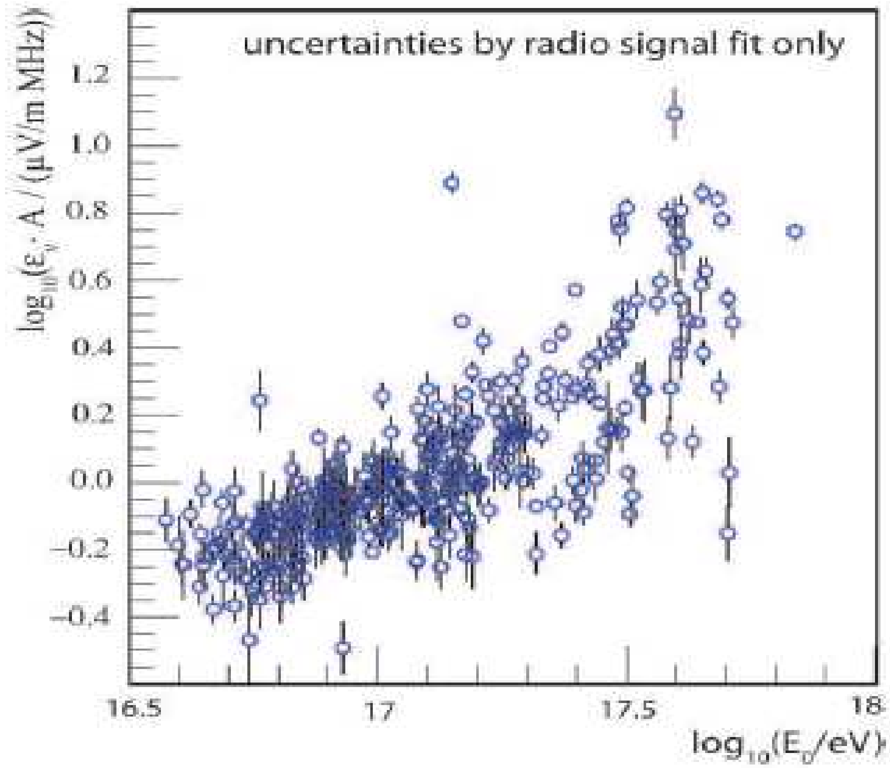
Numerical phasing



LOPES 10: Results with KASCADE-Grande



Correlation of the radio pulse height with the mean distance of the shower axis



Correlation of the radio pulse height with the primary energy of the shower

$$\varepsilon_{est,E_p} = (12 \pm 1.8)\left[\frac{\mu V}{m\ MHz}\right](1 + (0.1 \pm 0.03) - \cos(\alpha))\cos(\theta) \times \exp\left(\frac{-R_{SA}}{(200 \pm 45)m}\right)\left(\frac{E_p}{10^{17} eV}\right)^{(0.91 \pm 0.07)}$$

Norm
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Present & futur developments of the radio-detection with CODALEMA

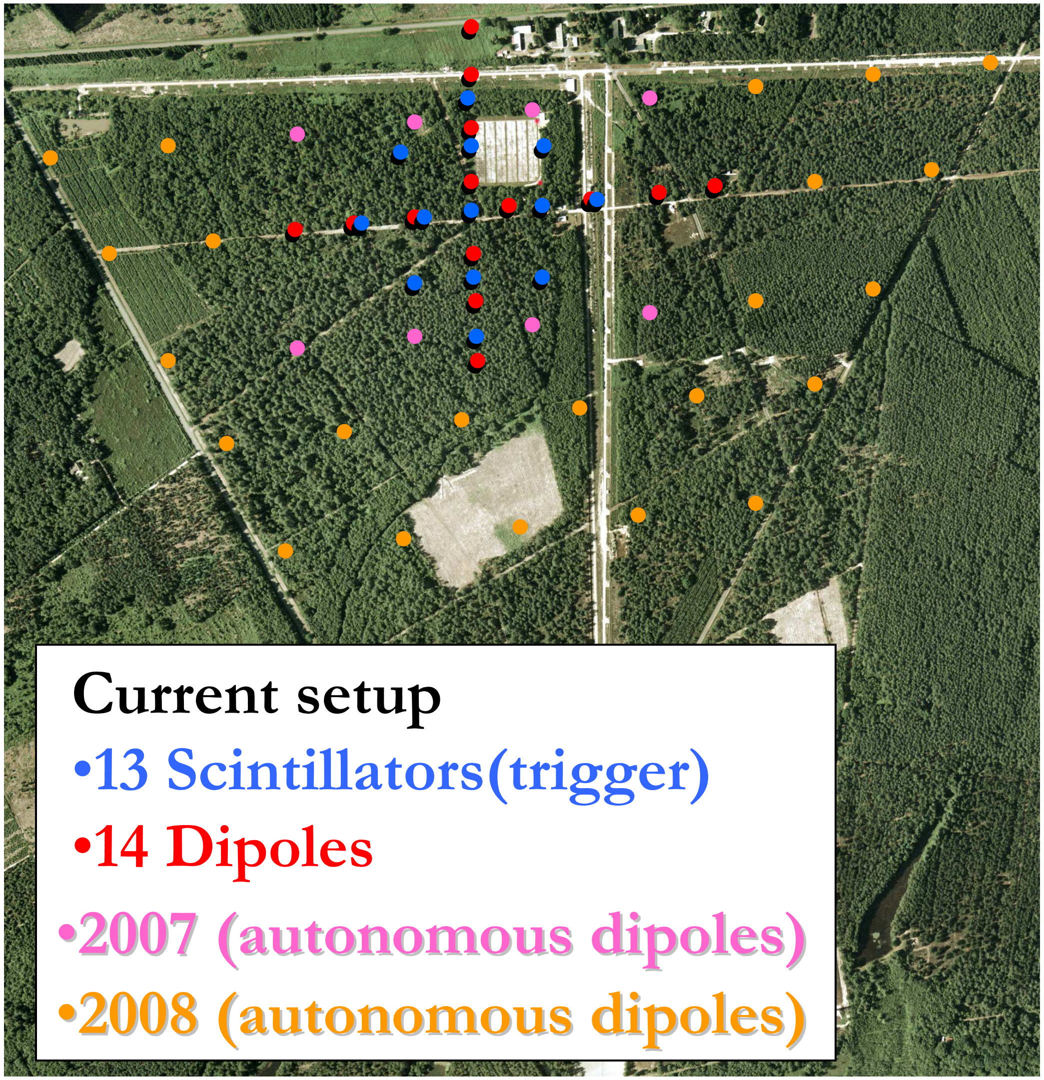
Schedule @ NANÇAY (ANR 2006-2008)

Evt by evt energy calibration < 10^{18} eV before end of 2008

Setup of a 1 km² engineering array for a future giant radio-detector (10x10 km² ?)

Autonomous dipoles:

- trigger,
- data taking (ADC MATACQ 12 bits, Full Bandwidth 0-250 MHz)
- Time tagging
- data transmission,
- power supply



Signal simulation @ 10^{20} eV

Vertical shower (charge excess only)

amplitude => énergy

duration => impact parameter

shape => Primary nature

SENSITIVE to XMAX

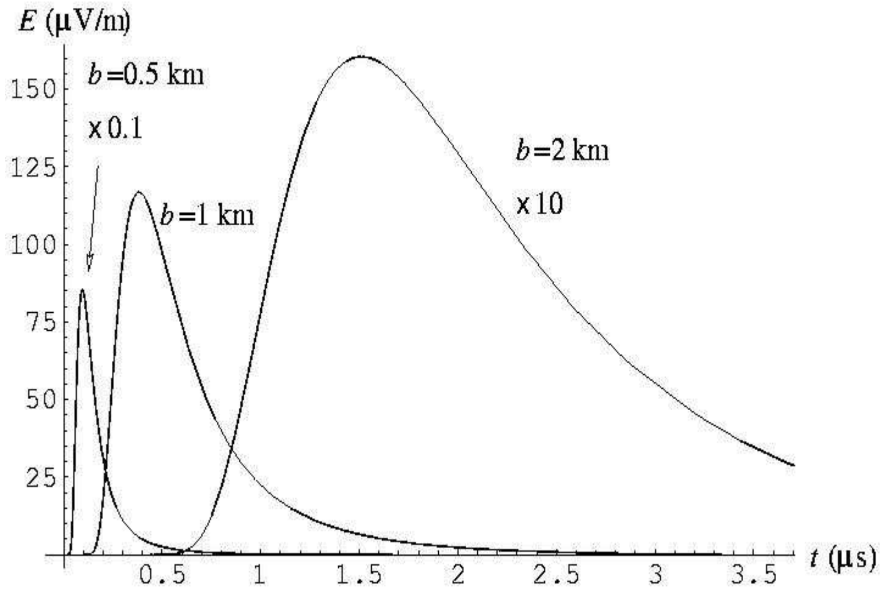
For detection at large distance

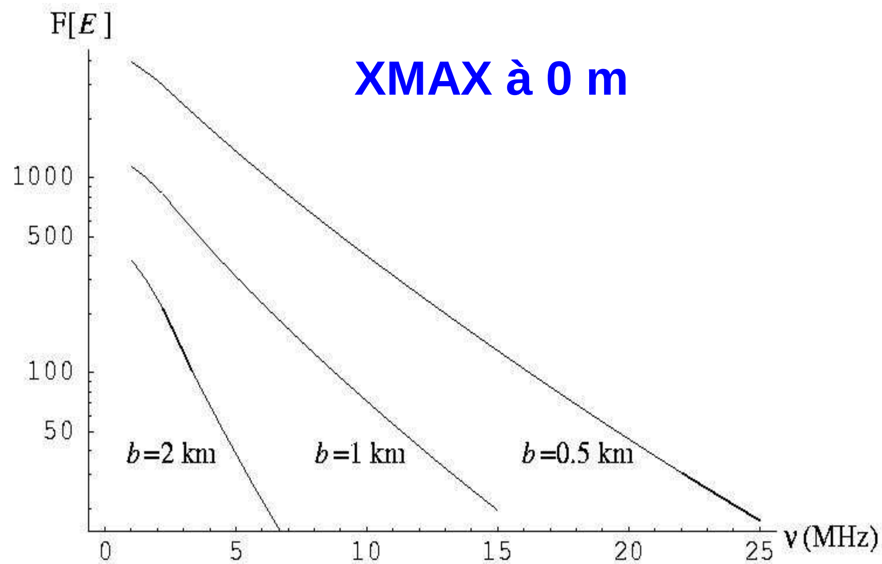
Broad-band dipoles

+ Autonomous

+ self trigger

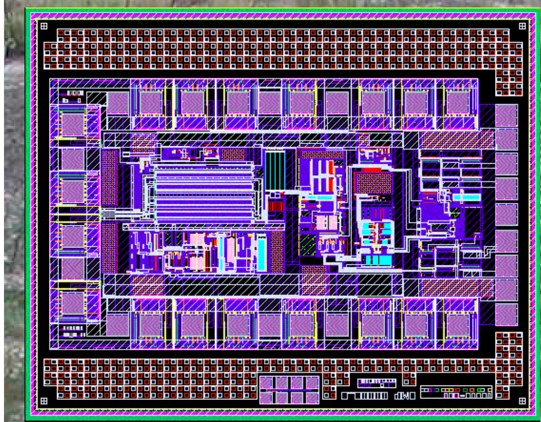
Charge Excess=10 %

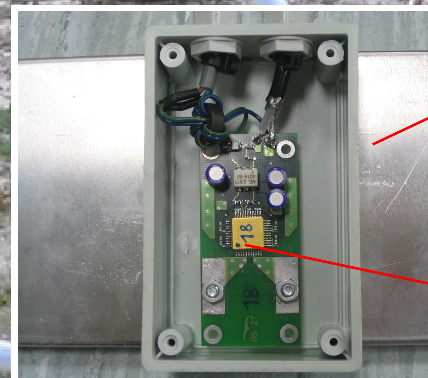




The CODALEMA short active dipole (1)

A dedicated LNA(ASIC)



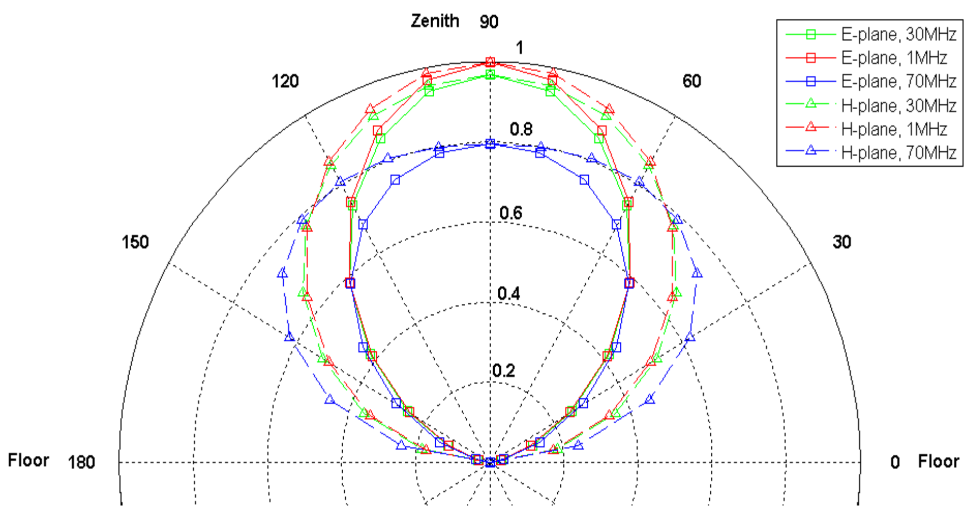


+ ADC MATACQ (12 bits, up to 1 GS/s, 2500 Samples)

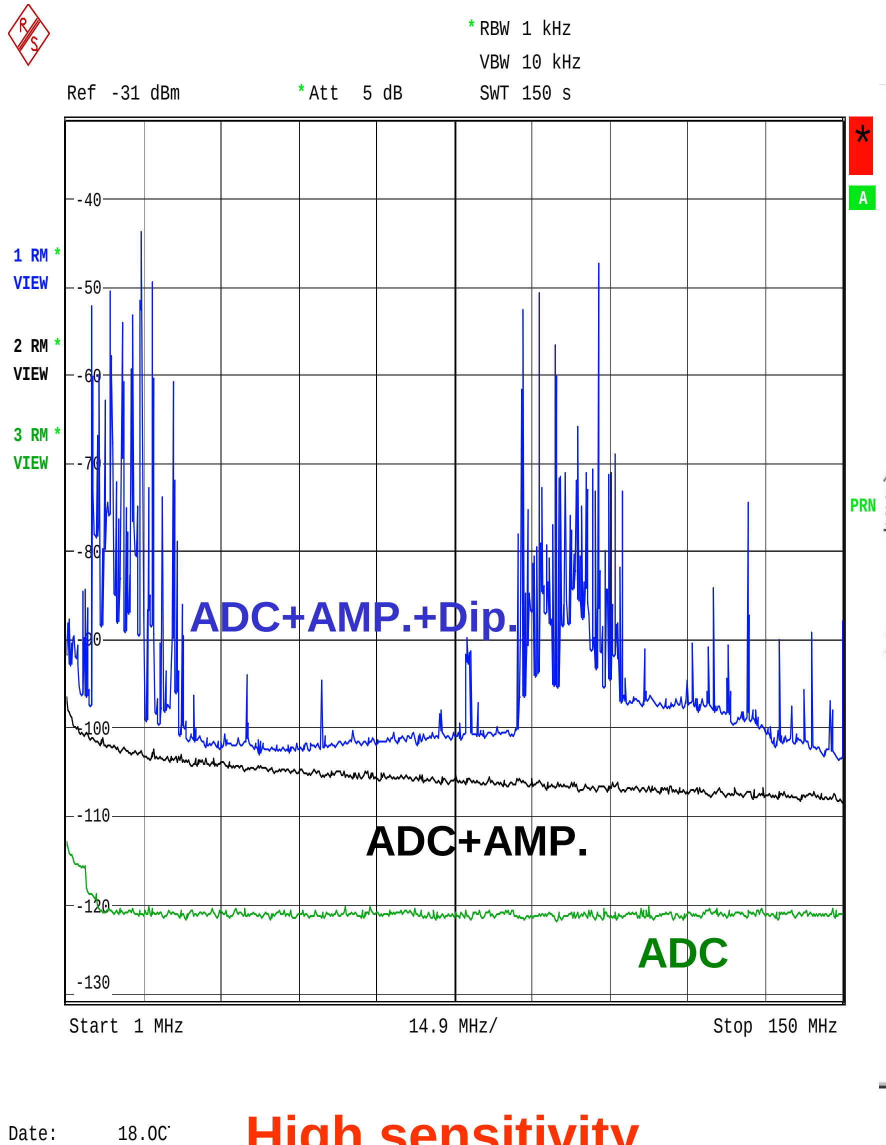
+ Full Bandwidth (0-250 MHz)

Constant directivity

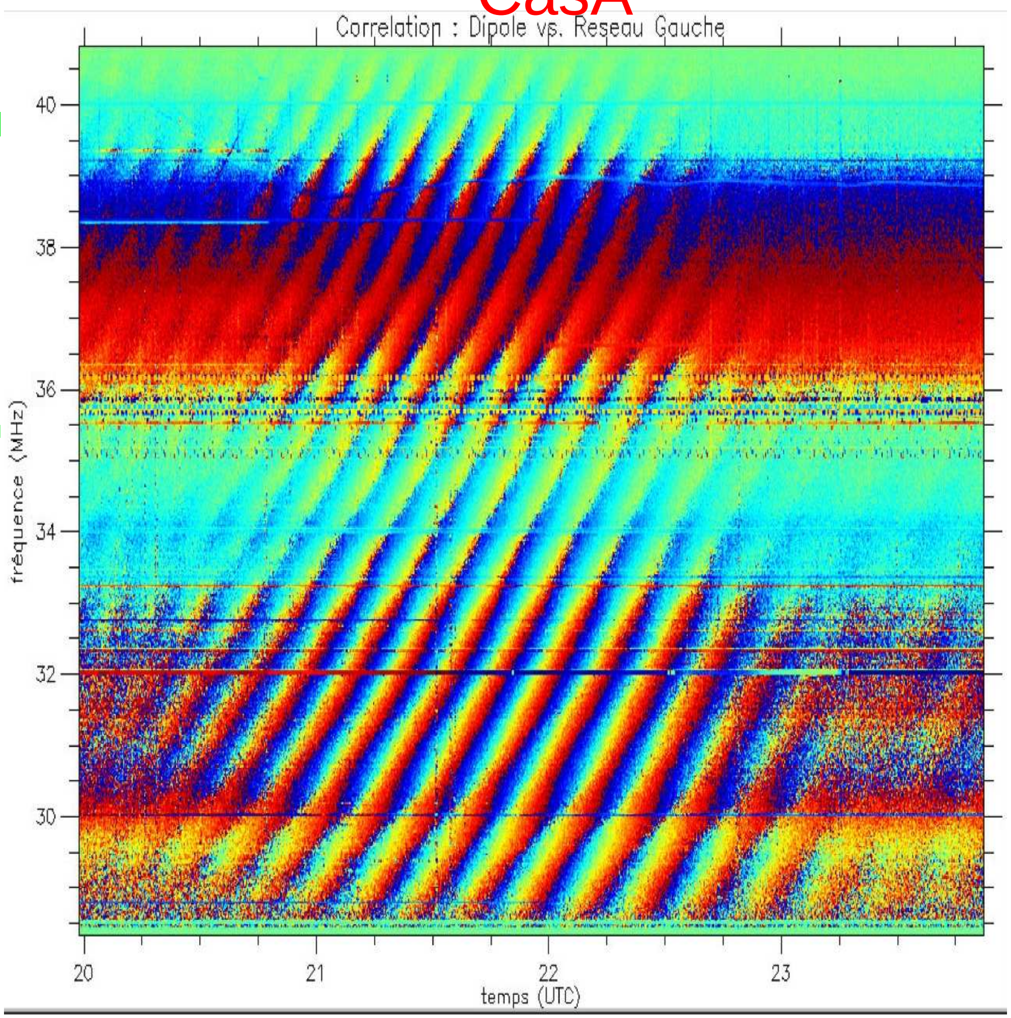
Normalised gain in E and H plane versus the Elevation angle



The CODALEMA Short active Dipole (2)



Interférométry Dipole-DAM
CasA

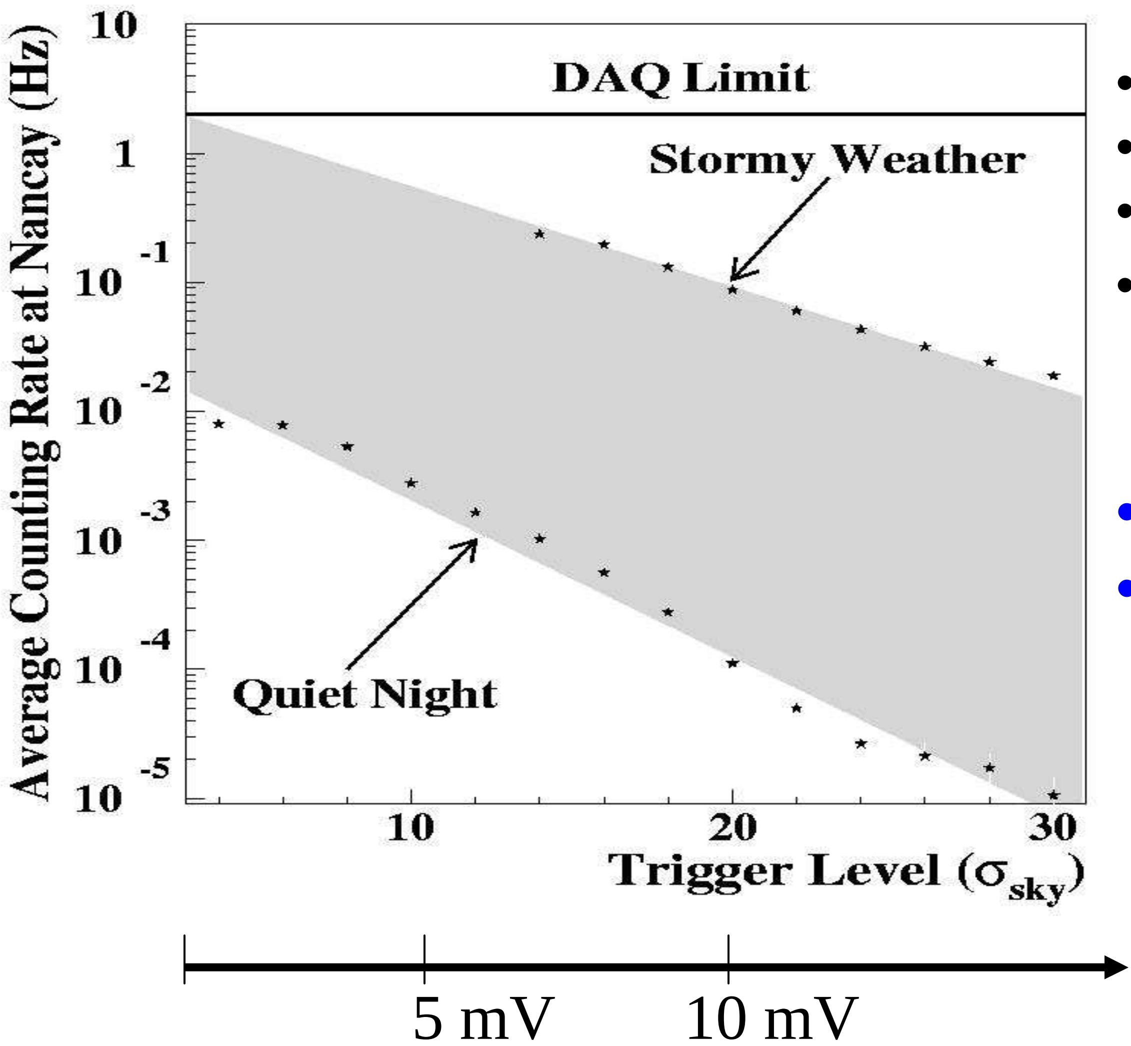


High sensitivity wide bandwidth

Very good astronomical performances on a wide band

Trigger rate in 33-65 band with 1 antenna

Knowledge of the transient radio background



- Atmosphéric conditions
- Day-Night modulations
- Human activities
- Solar activities

- **Low rate < 1 Hz**
- **100 % duty cycle**

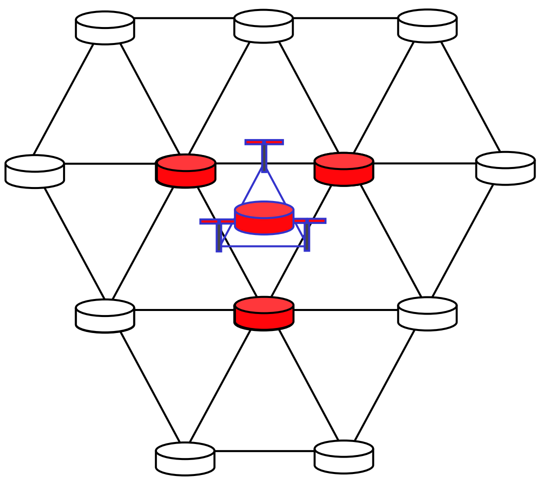
Trigger with antenna is possible in stand alone mode

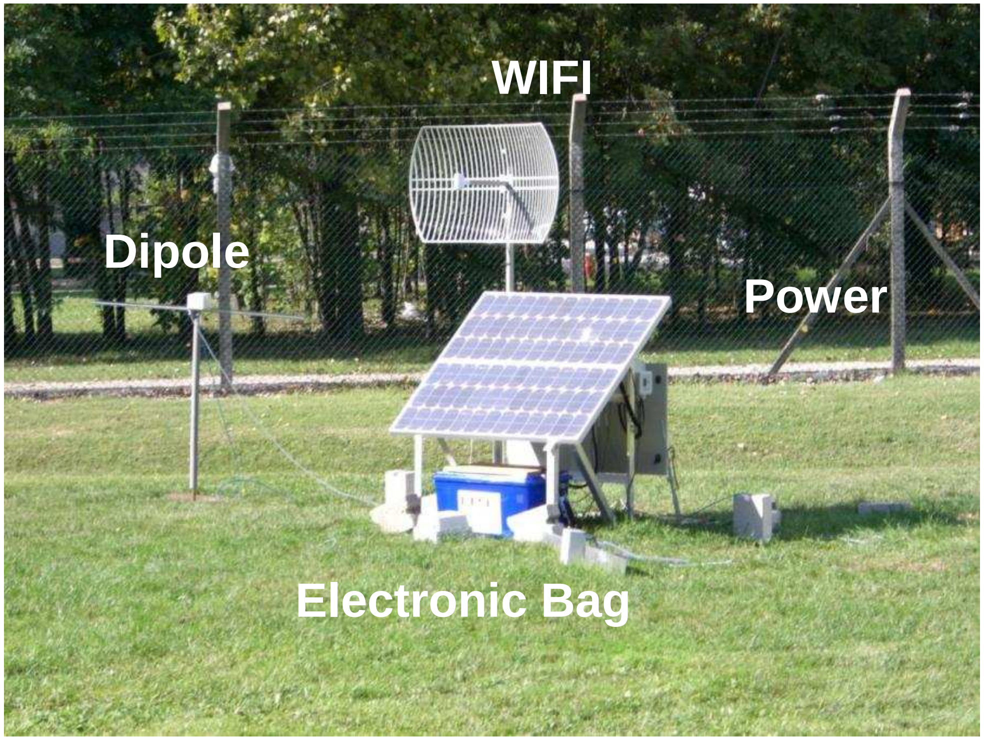
Radio Measurements at PAO

Test of radiodetection @ > 10^{18} eV in coincidence with PAO

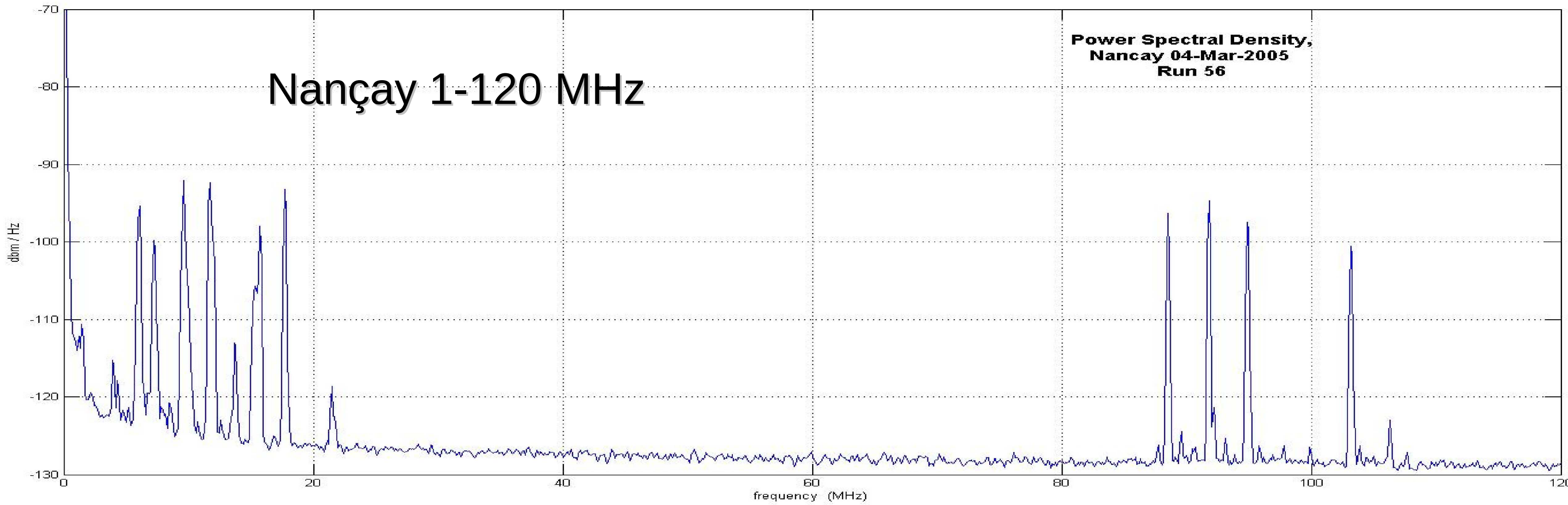
- **3 Autonomous Self-Triggered Broad Band Dipoles**
- **Off-line coincidences with PAO**
- **Electric field extension**
- **Energy Calibration @10^{18} eV**

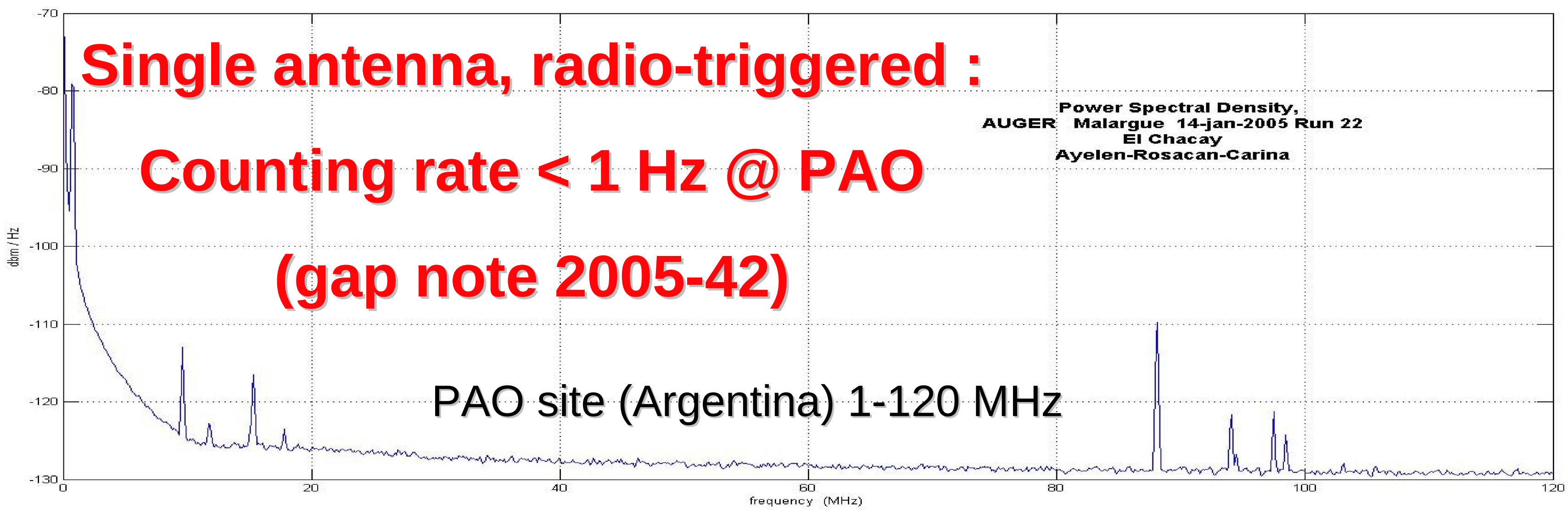
Installed since Nov. 2007 @ PAO





Sky background @ PAO (2005)





Single antenna, radio-triggered :

Counting rate < 1 Hz @ PAO

(gap note 2005-42)

Investigations parallèles dans l'ANR

Radio-Astronomie impulsionnelle (Obs. de Paris-Nancay)

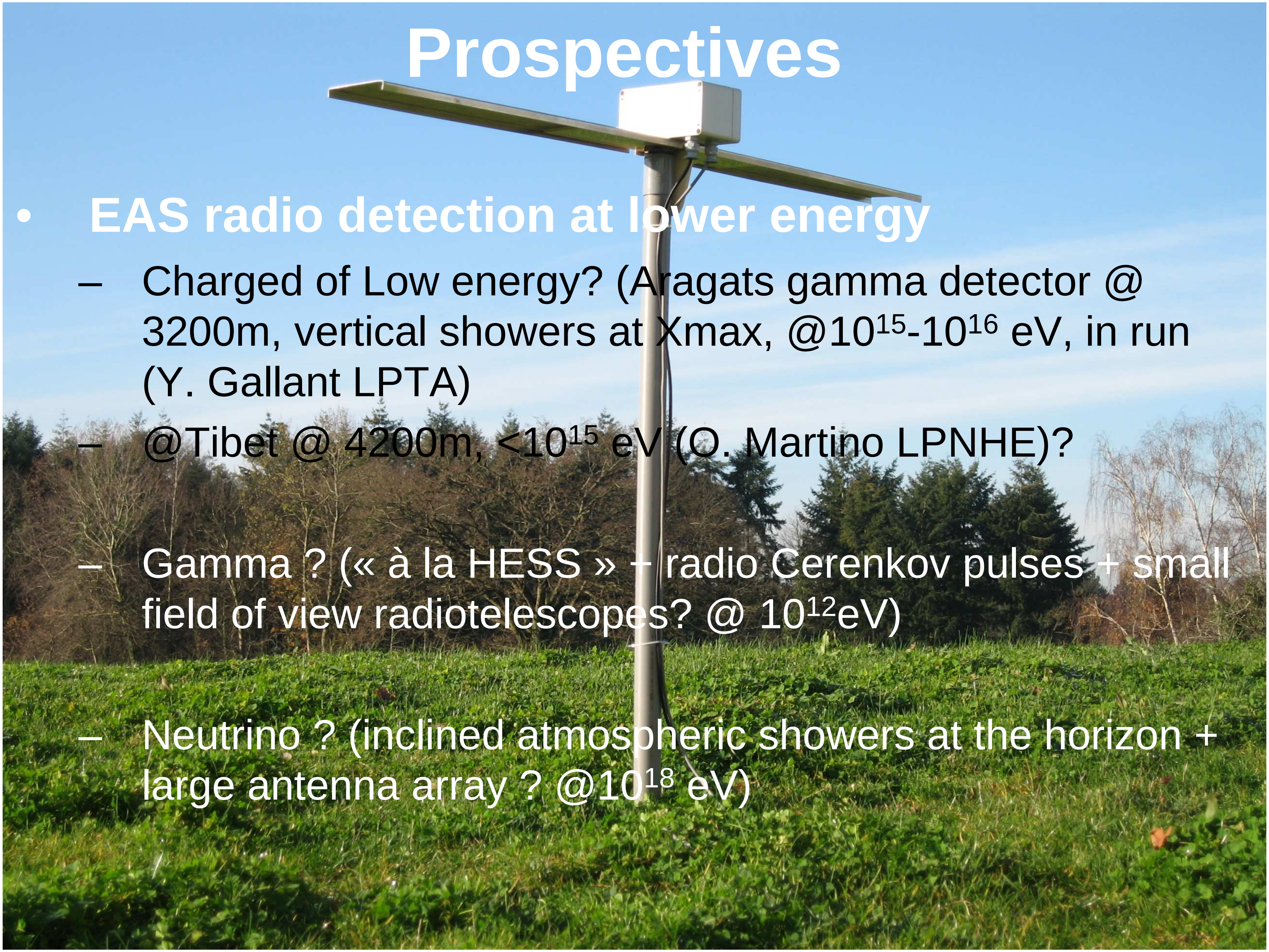
- DAM numérique (radiotélescope 2π.sr + phasage numérique + technique du snapshot pour s'affranchir des turbulences)
  - Détection EAS < 10^{16} eV
  - Imagerie
  - Pulsar Giant pulses, Solar burst,… unknown sources … Gamma showers (« à la HESS »), …

Physique de l'Atmosphère (LPCE Orléans)

- Décharges: Eclairs, Elfes, Sprites, Blue Jet, Elve, γ Flash, seismology…

Hors ANR (budget)

Test de detection sur Auger-Sud



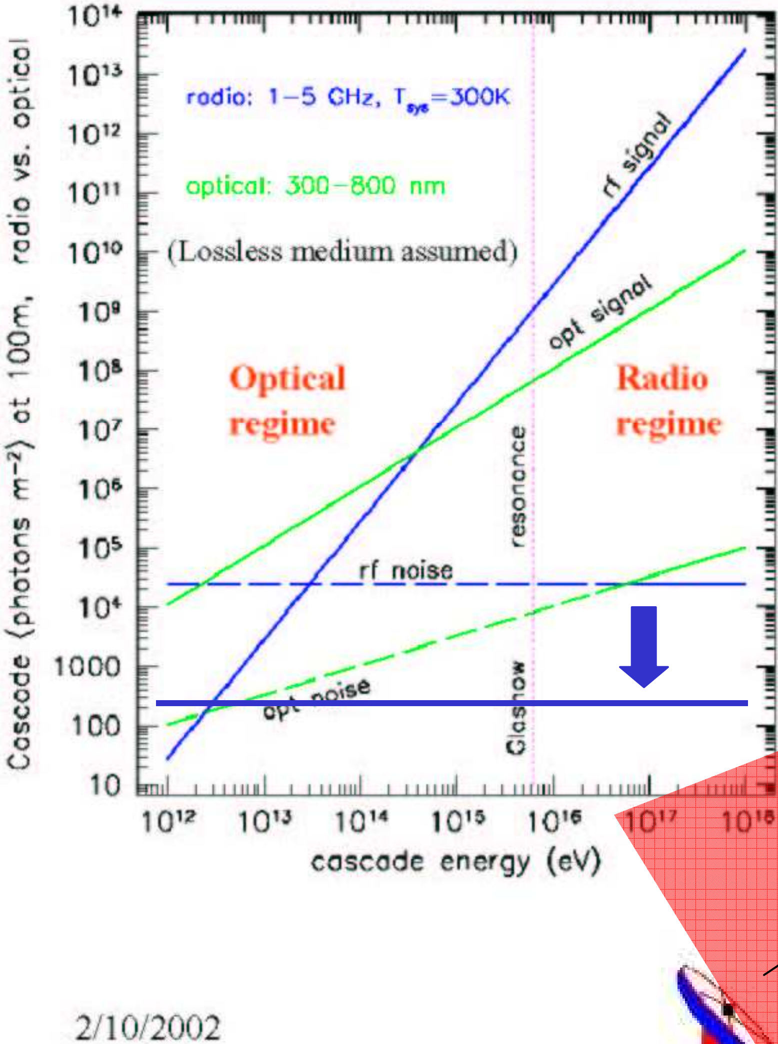
Prospectives

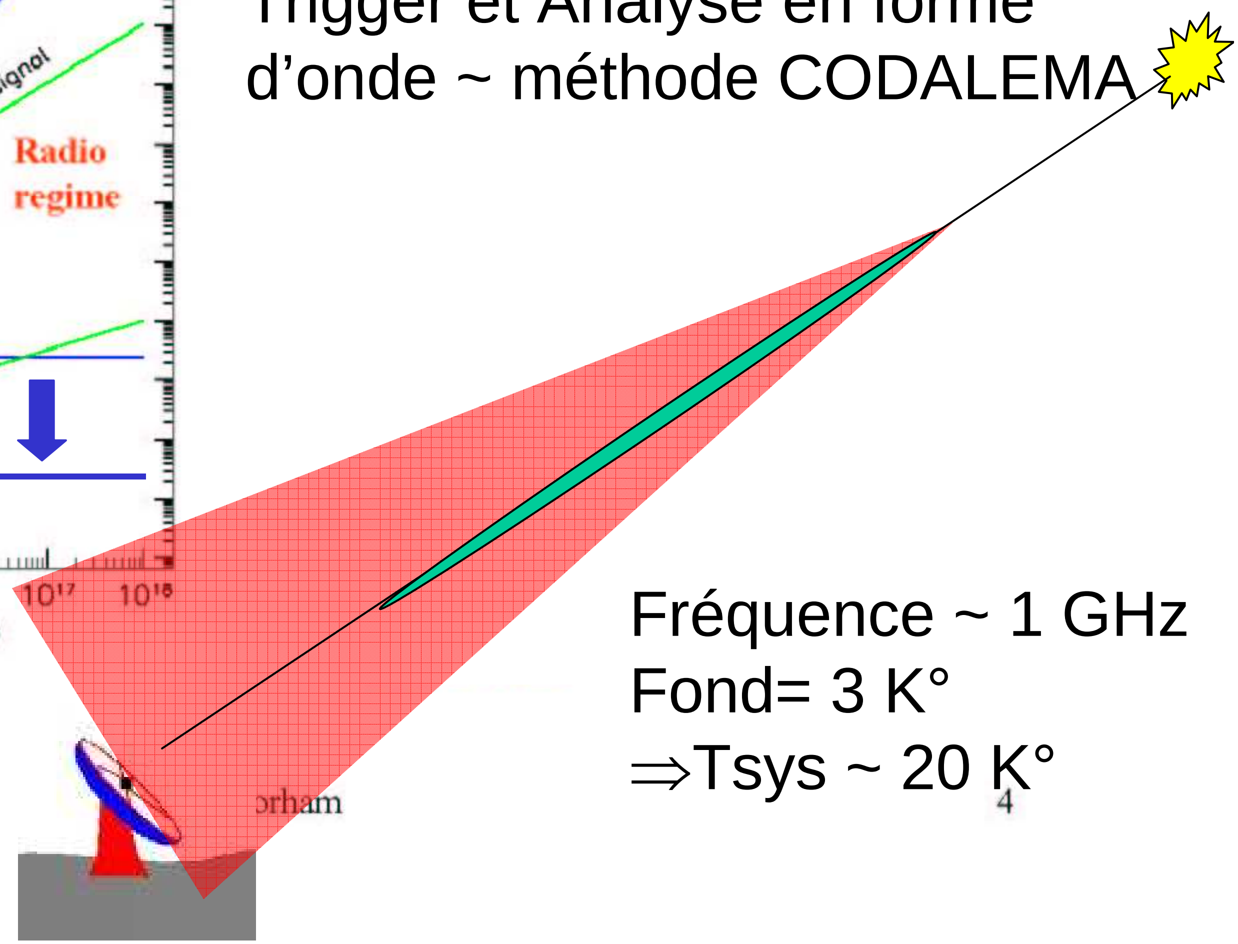
- **EAS radio detection at lower energy**
  - Charged of Low energy? (Aragats gamma detector @ 3200m, vertical showers at Xmax, @10^{15}-10^{16} eV, in run (Y. Gallant LPTA)
  - @Tibet @ 4200m, <10^{15} eV (O. Martino LPNHE)?
  - Gamma ? (« à la HESS » + radio Cerenkov pulses + small field of view radiotelescopes? @ 10^{12}eV)
  - Neutrino ? (inclined atmospheric showers at the horizon + large antenna array ? @10^{18} eV)

Radio-Détection à la HESS vers 10^{12} eV ?

Télescope pointé (~mn d'arc @ RT de Nançay)

Détection du transitoire **č** radio
Trigger et Analyse en forme d'onde ~ méthode CODALEMA

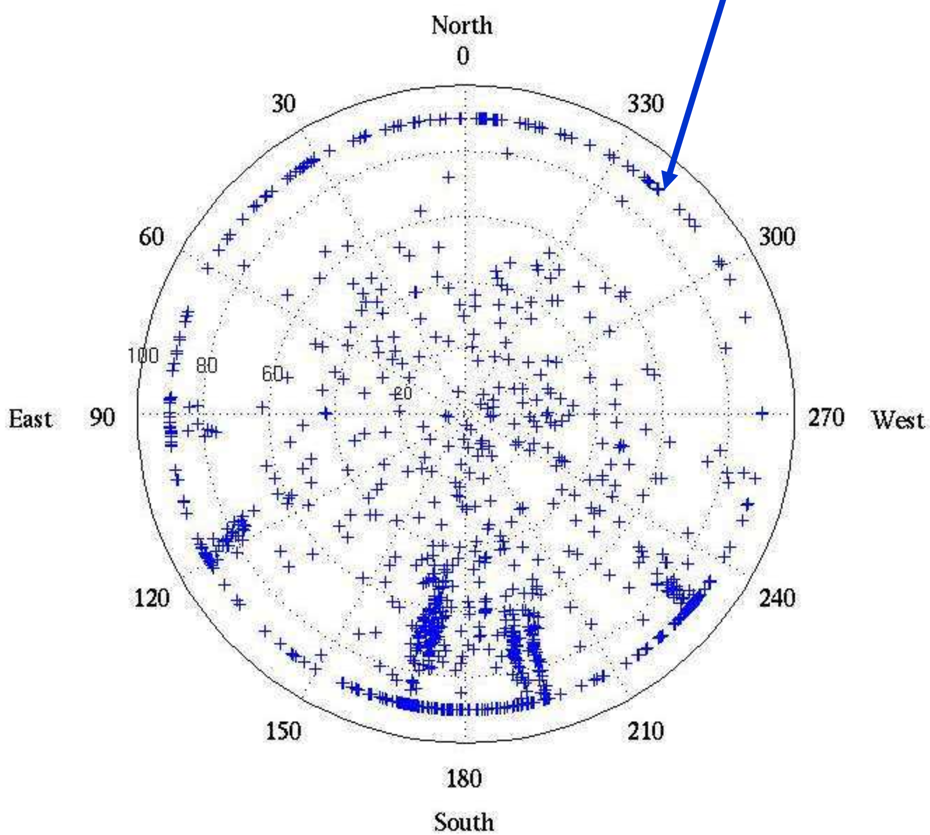




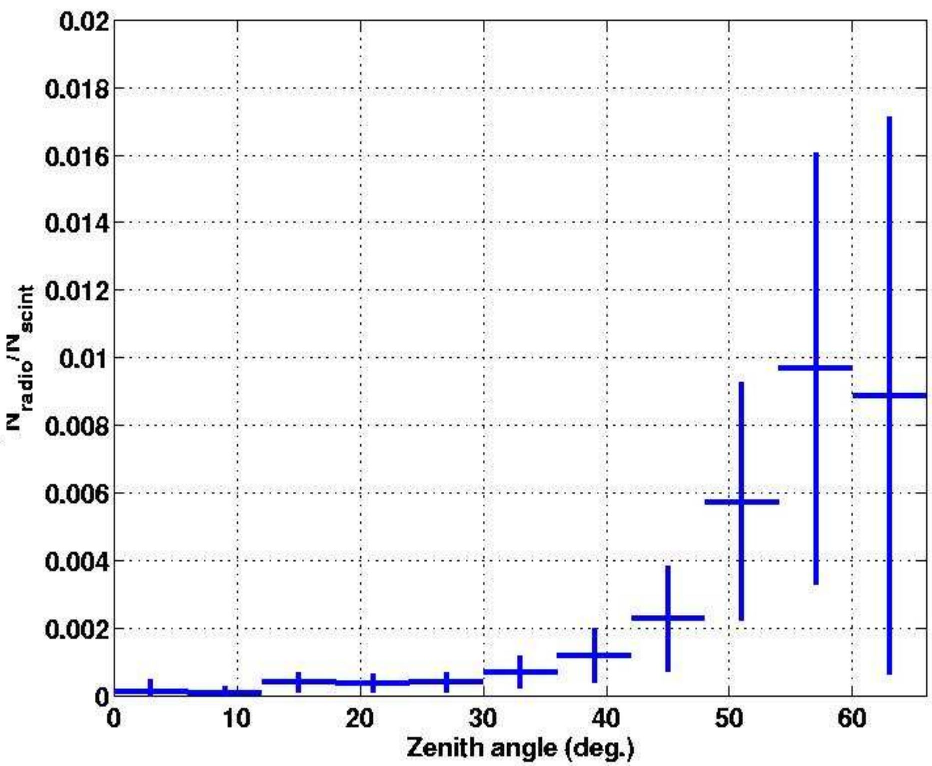
Fréquence ~ 1 GHz
Fond= 3 K°
⇒Tsys ~ 20 K°

Detection of horizontal EAS

Noise events in a 2 μs window around the particle trigger (Anthropic + solar + storms +….???)



Radio / Trigger Acceptance

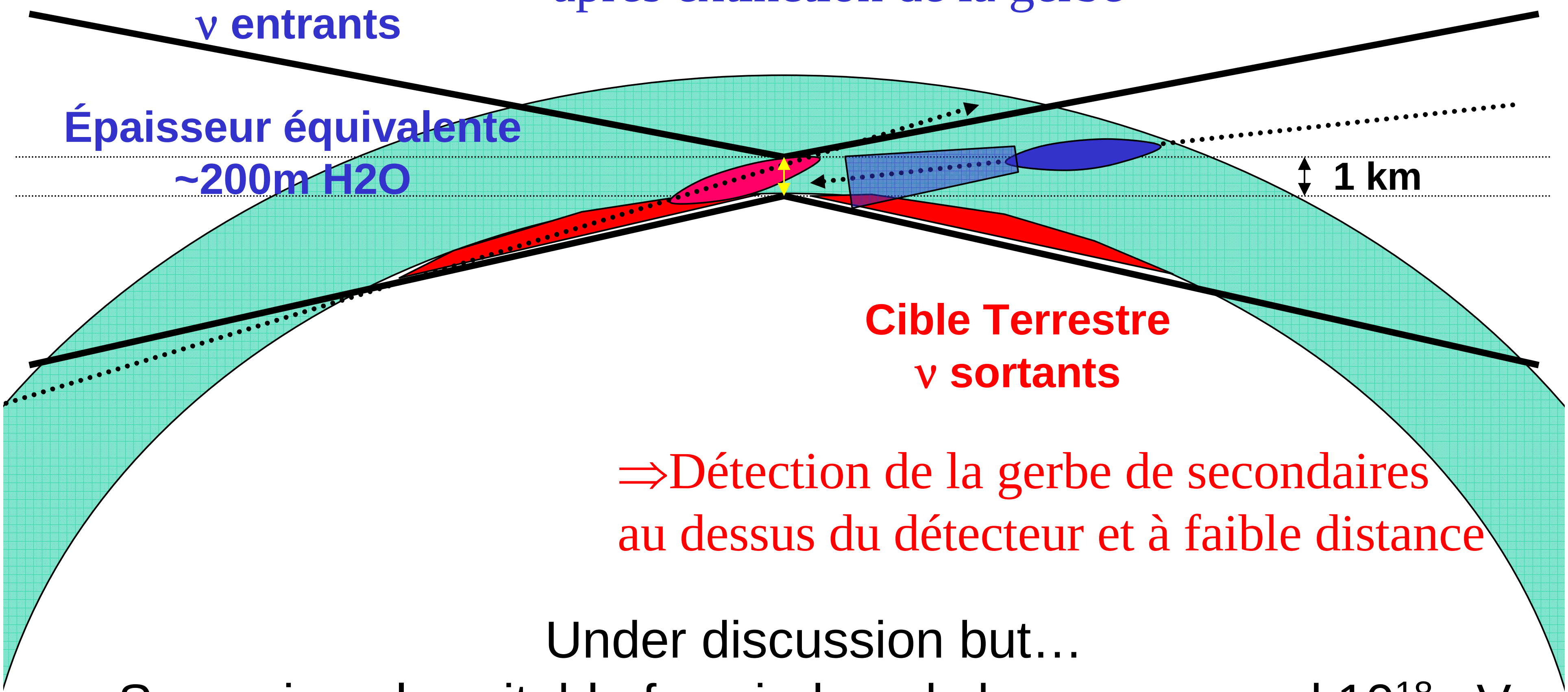


Radio-detection could be in nature adapted to the detection of atmospheric neutrinos ?

Détection de ν horizontaux

Set-up: réseau étendu

⇒Détection à grande distance par la propagation de l'onde EM après extinction de la gerbe



⇒Détection de la gerbe de secondaires au dessus du détecteur et à faible distance

Under discussion but…

Scenario only suitable for τ induced showers around 10^{18} eV